A Typical Radar Set
And Its Use
In Aeronautics

by

John Harold Shields

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Thesis

A TYPICAL RADAR SET AND ITS USE IN AERONAUTICS

BY

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INTRODUCTION

Purpose

On Tuesday, August 14, 1945, the United States War and Navy Departments released for the first time the entire story of radar. Since this time innumerable articles concerning radar have been published by leading magazines and technical journals, and the facts contained in this paper have been drawn principally from these sources.

The purpose of this paper is to present the general principles involved in radar circuits and equipment. But, before discussing the more technical phases we shall define the term radar and present a brief history of its discovery and early development. Because radar has been used in radio communication and nautical navigation there is mention made in this paper of its use in these fields, but the main emphasis will be in the application of radar to aeronautics.

Radar Defined

Radar is a special application of electronics to wartime purposes. It is an abbreviated form for the phrase "radio detection and ranging." The United States and Great Britain have accepted this term as a standard abbreviation and nomenclature for all radio direction and range finding apparatus. These devices are credited with saving Britain at the time of Germany's aerial blitz. By means of a radio signal "screen", approaching enemy planes were sighted and the British were able to alert fighter planes for the coming attack. Allied bombadiers, by means of tiny pencils of electromagnetic energy, dropped bombs on their targets with amazing accuracy when their objectives were invisible to the naked eye. Time Maga-

zine, issue of August 20, 1945, states that, "As a military threat, either in combination with atomic explosives or as a counter measure, radar is probably as important as atomic power itself."

The principle purpose and use of radar is in range and direction finding apparatus. The principle of radar is relatively simple and is easily understood. Electromagnetic waves of short wave length travel in almost straight lines, and like all electromagnetic waves, travel with the velocity of light, 3×10^8 meters/sec. A pulse of electromagnetic energy of short duration sent out into the atmosphere will travel outward away from the transmitter with the velocity of light, until it encounters an obstacle or an obstruction in its path. Generally, the obstacle will disperse the wave in many different directions, but it will reflect a small amount of energy back upon itself to the transmitter. The time taken for the wave to travel from the transmitter to the obstacle and back is a measure of the distance involved. If the transmitter is directional, then the position of the transmitter will indicate the direction of the "target."

There were many technical difficulties involved before an apparatus could be designed to send out directional radio waves of ultra high frequency of great power. Never before had there been the need for precision in the measurement of time intervals of one or two microseconds, but due to the extremely rapid velocity of electromagnetic waves an accurate measurement of distance could be obtained only by such accuracy of time measurement. Never had it been necessary to generate electromagnetic waves 10 or 20 centimeters long at power levels of 300 kilowatts or more, nor had it been necessary to receive impulses of the same wave length at well under 100 milliwatts. Yet, these were the specifications on the Army anti-aircraft radar sets, the S C R - 584's.

Radar posed many scientific and technical problems. Their solution was a triumph of scientific ingenuity brought about by the dramatic realization that such a solution would save nations and lives.

THE HISTORY OF RADAR

Radar Before 1940

The discovery of radar was not the invention of any one individual or nation. The idea of measuring distance by means of reflected radio waves appears to have occurred to many individuals of many nations at approximately the same time. These individuals worked independently to bring radar to its present state of usefulness. "The Germans and to a lesser degree the Japanese contributed heavily to the early development of ultra high frequency equipment needed for radar. The British pioneered in 'pure' radar research and first put radar to the test of war. The Americans have also made important contributions to radar research and have raised the whole art to an engineering and tactical level unequaled by any other nation."[1.]

The foundation for all radio and radar propogation was first laid in 1886 by Heinrich Hertz when he demonstrated that electromagnetic waves could be generated by physical apparatus and were reflected by certain obstacles. In the United States the first official recognition of the possibility of locating targets by means of elctromagnetic waves was made by Dr. A. Hoyt Taylor and Leo C. Young of the Naval Aircraft Radio Laboratory of Antacosta. They observed a distortion in the received signals due to the reflection from a steamer on the Potomac, while they were working on communications experiments. In June, 1930, the same two men observed a beat pattern when an aircraft was between one of their high frequency transmitters and receivers. In the same year these men were ordered to investigate the use

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1. "Radar - The Technique," Fortune (October, 1945), p. 142.

of radio to detect the presence of enemy vessels and aircraft.

The first equipment used was extremely bulky, requiring a large distance between transmitter and receiver, the presence of an aircraft being detected by the interference of the ground wave and the wave reflected from the target. Later, the Army Signal Corps, which had been experimenting with various types of beat detectors for approaching aircraft, began to experiment with aircraft detection by use of microwaves a few centimeters in length. The experiments were successful only when the object was close by, proving impractical for any military application. There was no means of producing waves of this wave length of sufficient power to carry any distance.

The first government fund of $100,000 was allotted to the Naval Research Laboratory in 1935, for the specific development of radar. By 1936 an apparatus had been developed which would successfully send and receive reflected radio beams from passing aircraft. A successful demonstration of the use of a radar set in tracing bomber paths was performed before the Secretary of War and the members of Congress in 1937. Soon after, the Signal Corps Laboratory was established. Here tansmitting tubes were improved so that wave lengths could be reduced to 1½ meters, and a direction-finding technique was introduced which led to the automatic aiming and firing of antiaircraft guns.

By November, 1938, radar was able to locate airplanes for ground batteries; in tests performed at Fort Munroe, Virginia, the set detected antiaircraft shells in flight, and guided back to safety an Army bomber blown out to sea during a test mission as a radar target. By 1939 a set

designed at the request of the Air Corps showed a range of more than a 100 miles in tracking a bomber.

Wartime Development in Radar

When the National Defense Research Committee was set up in 1940, an agreement was reached between the United States and Great Britain pertaining to the free exchange of scientific information of a military nature. The British, under the imminent threat of war, had made rapid progress in "radiolocators" for use in coastal defense, and had developed the cavity-magnetron - a diode used in conjunction with a magnetic field - which could produce electromagnetic waves of less than 1½ meters wave length, but with high power. The tube was turned over to the United States and became a part of the United States' program of radar development in 1940.

During the next five years the concentrated efforts of the Radiation Laboratory at Cambridge, Massachusetts, General Electric, Westinghouse, Philco, Western Electric, and many other industries which cooperated with the Army and Navy, gave the United States and her Allied forces throughout the world, "eyes" to rout the enemy and end the war.

(A) Air Defense

"Radar is the basis of the defense against aircraft attack . . . A high flying plane is difficult enough to see visually even under the best conditions and to find its range by the optical means that were the only ones then at our disposal was always hard and sometimes impossible."[2]

2. Office of Scientific Research and Development, Radar A Report On Science At War, p. 1

When the British defended themselves against German aggression they had neither the personnel nor the planes to keep patrols aloft constantly. They had radar chains set up along the coast to "spot" the raiders miles away, take to the air and intercept the attackers. The British report that, "Night fighters directed towards their quarry by radiotelephones from ground radar stations finally found and chased the enemy aircraft or flying bombs by aid of their own smaller radar sets."[3] The radar sets were relatively independent of rain, smoke, fog and darkness. Fighters were alerted by ground crews as to the general direction of the enemy, and thus left on their own to find the approaching planes. But, when the weather was bad, ground radar technicians "spotted" the enemy, alerted crews, and directed them to strategic positions to fight enemy aircraft by following all action on his radar screen.

In 1940, most of the radar equipment operated at a wave length of 1½ meters. The sharpness of the target location depends largely upon the wave length of the beam used; for a given antenna size the sharpness increases as the wave length decreases. Before the war ended radar sets were in use that could spot enemy aircraft, follow it, and direct the fire of anti-aircraft guns with an accuracy of 0.6 degrees. The wave lengths used were about 10 or 11 centimeters. These sets were used against buzz bombs that were set to go in one direction and could not deviate from that path, thus making excellent radar targets. The spotter picked up the track of the bomb, determined its path, calculated its future position, and fired at it.

Radar sets were used at sea although the rolling, pitching, and

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3. Released by the British Information Services, Radar, June, 1945

tossing of a ship complicated antiaircraft control. The ship changed direction and speed frequently. In general, there would be several ships in a convoy; to make effective the use of radar, each ship in the group had its own radar set, and a means of coordinating information among the ships. If an aircraft carrier were one of the group each carrier plane would be equipped with a radar set and communication with the carrier. The further development of sea defense is a story in itself and not discussed in this paper.

(B) Air Offense

"Beginning as a purely defensive weapon, radar changed the face of the war more than any other single development since the airplane . . . Yet it had become by 1944 a superlative weapon of offense."[4] As previously meantioned, the sharpness and the accuracy of a radar set for a given size antenna is determined by wave length. The size of an airborne radar set is limited to begin with, and the value of a microwave set was obvious to all who considered the problem of airborne radar sets.

England, interested in protecting herself, was concerned with defensive equipment, spotting networks and protective units; the United States was not tied down so rigorously and decided in favor of the development of offense equipment. No attempt is made in this paper to go into much detail about the success of offensive radar but a general picture will be given.

Whereas submarines had been able to surface nightly to recharge their batteries and take on air, the use of radar made this habit dangerous, as

4. Wesley W. Stout, The Great Detective , p. 2.

submarines could be easily discovered. Radar cannot take the entire credit in submarine destruction because of vast improvements in the quality of explosives and torpedoes, but radar gave vital aid in placing and directing these missiles.

Japan was successfully isolated from the world when the Fourteenth Air Force sank 110,000 tons of Japanese shipping in the China Sea in a single month. This was achieved entirely at night and entirely by radar. Radar was invaluable in the bombing of factories, munition dumps and transportation lines. Weather conditions over Germany made it necessary many times to work entirely by radar. Microwave airborne radar sets located mountain peaks, rivers, cities, buildings and railroads with precision and accuracy, allow - ing continual and uninterrupted bombing.

Radar sets were excellent position locators. Ground crews directed fighter planes and medium bombers so that the pilots would know enemy territory or allied troops. Radar was invaluable in the Battle of the Bulge, where weather was overcast and the distance required to fly over enemy forces was only a matter of minutes. Thus we helped to win a war with a great and efficient Air Force equipped with radar.

TIMING CIRCUITS

The most essential and important function of the radar set is the accurate measurement of time, since the time required for electromagnetic waves to travel to and from a target, may be converted immediately into distance; therefore, a major part of the radar set is involved in some type of timing measurement or control. Timing circuits must be used to synchronize the transmission and the indicator circuits, to delay or advance the stages involved in range measurement, and to modulate the ultra high frequency energy being transmitted. As previously mentioned, timing circuits must be extremely precise; an error of only a millionth of a second in synchronizing the indicator and the transmitter causes an error that may be calculated in distance as 327 yards. Prior to World War Two, methods for measuring time intervals in microseconds were known but undeveloped. Before the War ended, these methods had been developed until we were able to measure time "with an accuracy which corresponds to only 5 or 10 yards or about one-thirtieth of a millionth of a second."[5]

Simple Oscillator Circuits

Any radar set may be classified as (1) one which is controlled by a separate oscillator unit and (2) one which is self synchronous. The former set is the more stable and accurate of the two. The latter set results in output waves which may not be too sharply defined, and may vary in frequency from one cycle to the next, due to lack of stability; however, sets of this type tend to be more simple in design and more easily assembled than

5. Office of Scientific Development, Radar A Report On Science At War, p. 3.

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1. Office of Scientific Development, Radar A Report on Science at War, p. [illegible]

master oscillator types.

This section will be devoted to the master oscillator type, or type one, in which all timing circuits are controlled by a separate timing mechanism.

The operation of the radar set depends upon the release of small bursts of electromagnetic energy of short wave length for a short pulse duration period, after which the set remains quiet while it "listens" for energy reflected back to it by some object. The pulse duration and the quiescent period together constitute a complete cycle of operation. The number of complete cycles per second is called the pulse recurrence frequency.

The pulse recurrence frequency of the set will be determined by the use to which the set is put, and generally the pulse recurrence frequency will be established by the frequency of oscillation of the master circuit. Since the pulse recurrence frequency is usually between 500 and 5,000 pulses per second, the oscillator need not be crystal-controlled. In many sets, due to the inherent stability of crystal-controlled oscillators, crystals of high natural frequency have been used, and then by adequate frequency dividing circuits the oscillations are brought within audio-frequency range.

There are many ways to produce stable sine wave oscillations. All Hartley, Colpitts, and tuned-grid tuned-plate circuits can be used, providing a large impedance is placed between the plate and the oscillating circuit, to act as a stabilizer. One of the most effective methods is that which uses a bridge circuit as a stabilizer (Fig. 1).

The operation of the Wien bridge is quite simple. Degenerative feedback is applied to the amplifier through an impedance bridge. Since the output of the Wien bridge is zero at resonance the inverse feedback and

master oscillator boxes.

This section will be devoted to the master oscillator boxes, or tape-ons. In which all timing circuits are controlled by a separate timing generation.

The operation of the radar gas cascade uses the relation of small bursts of electromagnetic energy of short wave length for a short point duration period, after which the gas remains quiet while it "listens" for energy reflected back to it by some object. The pulse duration and the quiescent period together constitute a complete cycle of operation. The number of complete cycles per second is called the pulse recurrence frequency.

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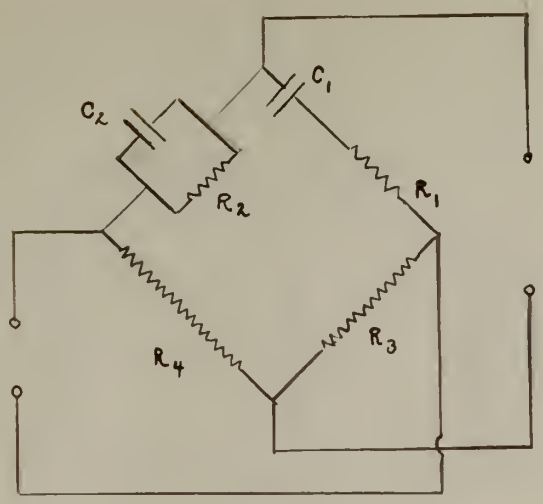
Some are made to produce stable sine wave oscillations. All vacuum, gaseous, and thermo-ionic thermo-joint circuits can be used, providing a linear frequency is given between the plate and the oscillating circuit, to act as a stabilizer. Due to the most effective method is that which uses a bridge circuit as a stabilizer (Fig. 3).

The operation of the first bridge is quite simple. Degenerative feedback is applied to the amplifier through an impedance bridge. Since the output of the first bridge is zero at resonance the inverse feedback and



(Fig. 1). Wien Bridge.

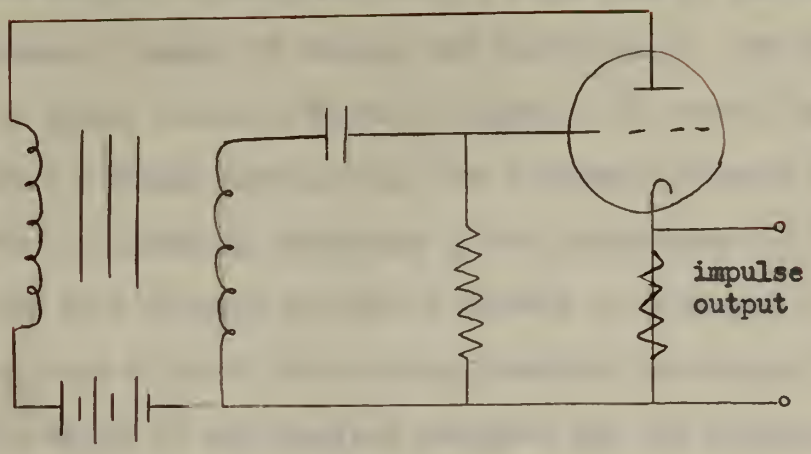
the amplification factor of this tube are a maximum at this frequency. If the positive feedback through a suitable regenerative network of the same circuit is great enough, self-induced oscillations will take place at the resonant frequency of the bridge. It can be shown that the resonant frequency of the Wien bridge is given by the expression

$$f = \frac{1}{2\pi r_1 c_1} \quad \text{where } r_1 = r_2 ; r_3 = 2r_4 ; c_1 = c_2$$

Thus, merely by adjusting r_1 we can change the basic frequency of oscillation. The Wien bridge oscillations will have low harmonic content, high frequency stability, and almost constant output voltage.

A second method quite commonly used is the blocking oscillator circuit, a typical simplified circuit, shown in Fig. 2.

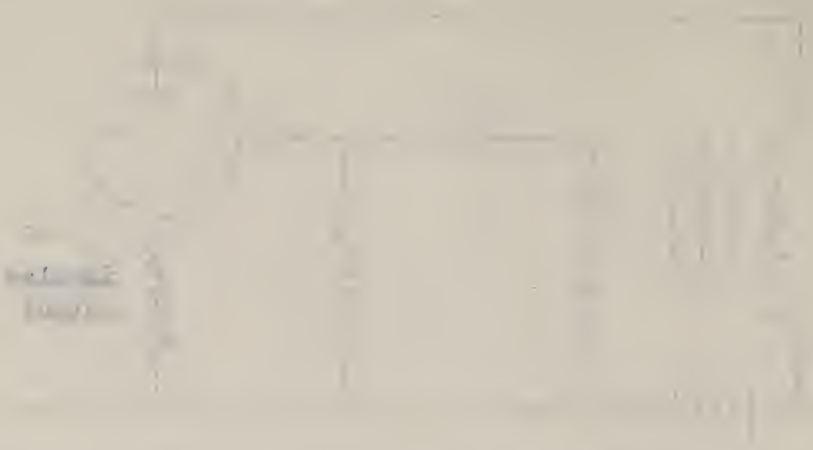
It is not necessary for the master oscillator to produce pure sine waves; the only requirement being that it should produce pulses at a regular recurrence frequency. Then the blocking oscillator can be easily adapted for use as the master oscillator of the radar set. The principal



(Fig. 2). Blocking Oscillator Circuit.

problem presented in the use of a blocking oscillator is that the period at which it will function is not easily determined prior to actual testing, but the oscillator can be used to generate a relatively sharp pulse of short duration, and therefore is highly important.

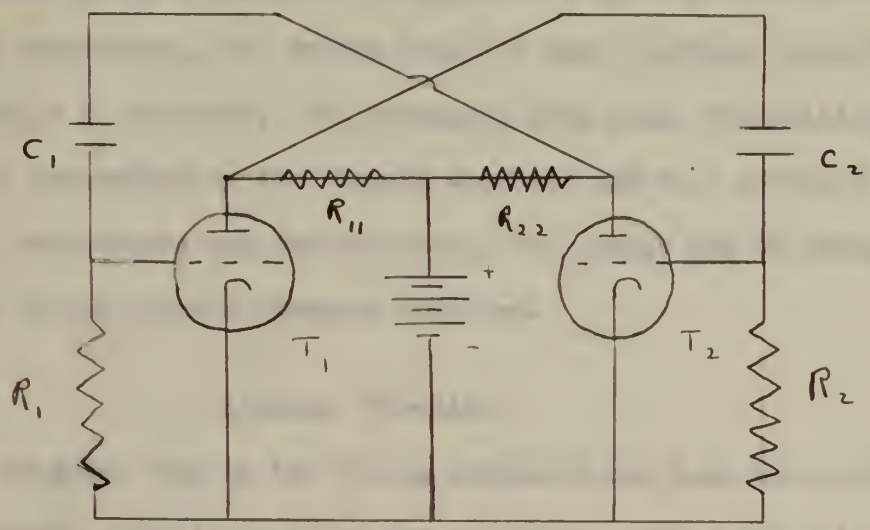
The blocking oscillator differs from the sine wave oscillator. When anode voltage is applied to the tube, the oscillation transformer coupling between the plate and the grid circuits causes oscillations to commence. If the grid is at its most negative value, increasing oscillation strength causes the grid to become rapidly more positive. When the grid actually becomes positive, with respect to the cathode, grid current begins to flow and begins to charge the condenser C. The charge on the condenser is such that it would make the grid negative, and while the grid is still positive, with respect to the cathode, the negative charge on the condenser builds up rapidly. The result is that the condenser, and consequently the grid, becomes negative enough to cut-off the plate current entirely. The



(Fig. 2). Blocking oscillator circuit.

circuit then refuses to oscillate until a large part of the negative bias on the condenser C leaks off through the resistance R. The cycle then repeats. By proper choice of circuit elements, the circuit may be made to block after a single oscillation. The frequency at which the pulses are generated is primarily determined by the capacitance and resistance values in the grid current, but this frequency is difficult to calculate, since the voltage to which the coupling condenser is charged depends upon the relative values of the coupling condenser and the magnetizing inductance of the pulse transformer.

Another common type of oscillator circuit used in the radar set is a multivibrator (Fig. 3).



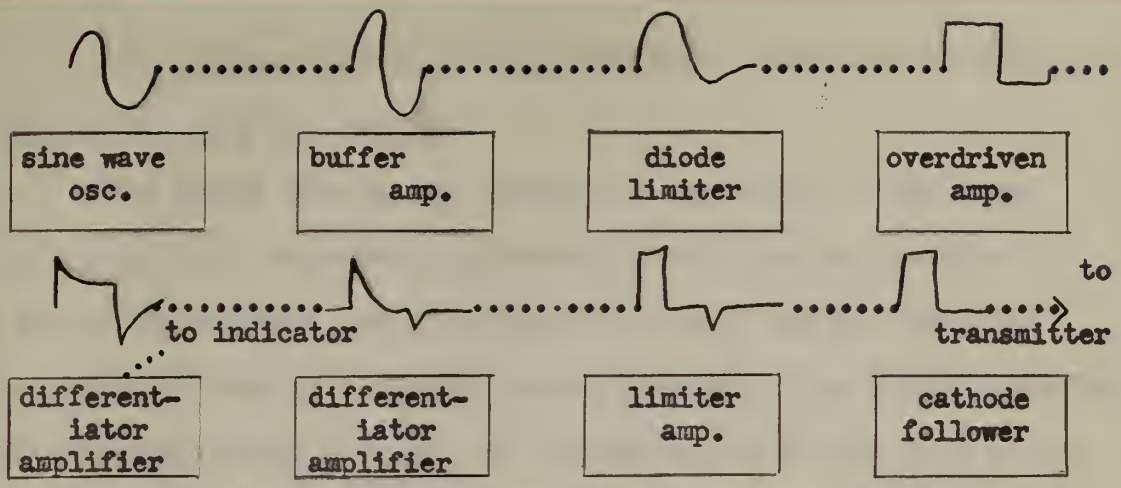
(Fig.3). Simple Symmetrical Multivibrator Circuit.

Its operation depends upon feedback between the two tubes, shown coupled in the usual R-C manner. It is considered worthwhile to mention the details involved in the multivibrator oscillation, since this particular circuit is used not only in the master oscillator circuit, but also in

many other stages of the radar set. Let us say T_1 has just completed its cycle of oscillation, and T_2 begins to conduct a current. The voltage across T_2 begins to fall as the plate current grows, and since the changing voltage that exists across T_2 is impressed across R_1 and C_1 in series, the current begins to leak out of C_1 and into C_2. The flow of current through R_1 causes the grid of T_1 to become more negative, while the flow of current through R_1 causes the grid of T_2 to become more positive. Therefore, T_2 is prevented from conducting, and T_1 continues to conduct. As the condenser C_1 discharges and C_2 charges, the currents flowing decrease exponentially and the grid biasing voltage of T_1 eventually becomes so small that this tube conducts. The circuit "triggers" at this point, i.e. makes an abrupt change from one stage of operation to another stage. Since the circuit is symmetrical, the entire cycle is then repeated, except that T_1 conducts while T_2 cuts off. The frequency with which the multivibrator operates is determined by the circuit elements and will increase with decreasing resistances and capacitances. The output may be taken off across any of the circuit elements involved.

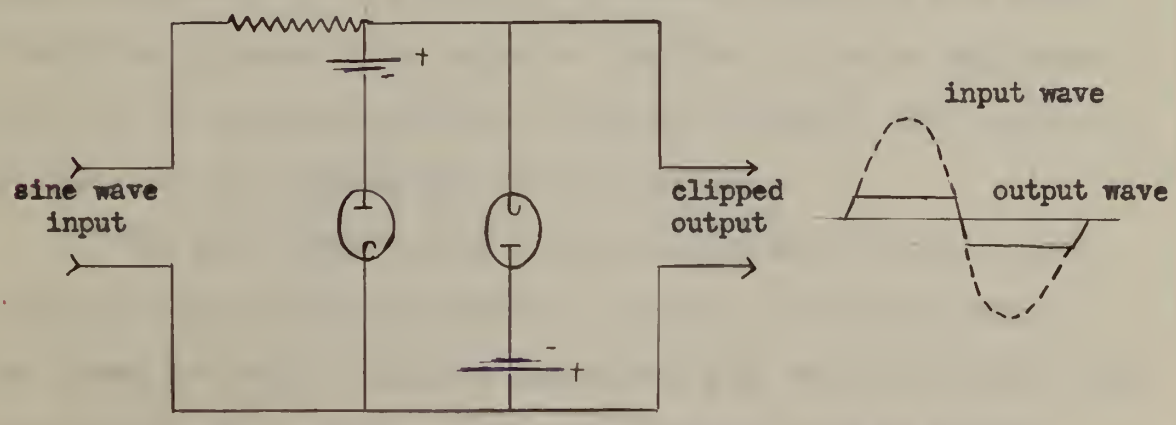
Clipping Circuits

The original step in the timing mechanism has been the production of a regular stable repetition frequency. However, before the pulses are used to "trigger" or control other sections of the set, they are usually passed through various amplifying, distorting, and pulse forming stages - the number of stages required varying greatly from one set to another. The entire process of pulse forming is schematically shown in Fig. 4 for the case in which the master circuit is a sine wave oscillator.



(Fig. 4). A sine wave oscillator. Sine waves occur at fixed frequency equal to pulse recurrence frequency of set. (From Jordan McQuay, "Practical Radar," Radio News, June, 1945, p. 41).

In this section we shall discuss "clipping circuits," i.e. those circuits used to flatten or cut off some part of the oscillation forms impressed upon it, and thus make the output pulses more rectangular. Clipping, or limiting, is not a new development in electronics. It has had many former uses. Indeed, frequency modulation has always depended upon some form of limiting action in the receiver, to remove amplitude modulation resulting from atmospheric disturbances.



(Fig. 5). Diode clipper with associated waveform.

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The simplest method of "clipping" makes use of the rectification properties of the diode (Fig.5).

The output voltage has exactly the same shape as the input voltage until the instantaneous impressed voltage reaches the bias of the diode. The current then flows into the diode, and the resulting voltage drop, through the high resistance R_1 prevents any other appreciable further rise in output voltage. By eliminating one or the other of the tubes we can clip a major portion of one section of the wave leaving the other section unchanged. The completeness with which clipping occurs depends upon the resistance of R_1 being much larger than the dynamic plate resistance of the diode.

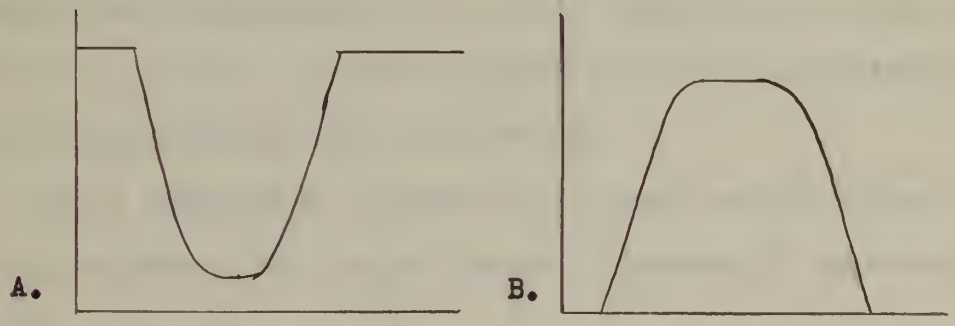
Clipping can also be accomplished by using triodes, tetrodes, or pentodes. Since the principles upon which the triode operates may be quite readily applied to the tetrode and the pentrode, the discussion will be confined to triodes.

The triode may be used as a clipping device, either as a violently overdriven amplifier or as a cathode follower. In the block diagram previously shown in Fig. 4, the cathode follower is used merely to match the impedance of the output of the timer to that of the transmitter, but it can also be used for clipping, in place of the overdriven amplifier - if the clipping need not be too sharp.

The basic understanding of the clipping action of the triode follows directly from our discussion of the diode. When oscillations from a previous stage are applied between the grid and the cathode of the triode, grid current will flow during the positive cycle of applied voltage. If the grid current is made to flow through a high resistance,

the over-all grid voltage will be unable to go highly positive, for the grid-cathode path will act as the diode limiter. Since the grid potential, with respect to the cathode, remains almost constant, the output plate current will be almost constant throughout the positive half cycle of applied voltage. When the grid goes below cut-off on the negative half cycle, the plate current will once again be constant at zero value. The net result is to make the output wave have a square, or box-like shape. If we so desire, we can impress this output upon another similar circuit and box the pulse even more.

The two output voltage waveforms (Fig. 6) illustrate the difference in effect between the overdriven amplifier and the cathode follower.



(Fig. 6). Waveforms of overdriven amplifier and cathode follower.

The obvious difference is that the flattening of the output wave is reversed in the two cases. With the overdriven amplifier the cut-off causes the top of the waveform to be flattened; with the cathode follower, the cut-off causes the bottom of the wave to be flattened.

With the overdriven amplifier the effect of the grid current flattens the bottom of the waveform; with the cathode follower, the grid current flattens the top of the waveform.

Only one more item need be mentioned in connection with the difference between the two clipping devices. The calculations of performance are usually easier with the overdriven amplifier than with the cathode follower.

Short-Time Constant Circuits

By means of a master oscillator circuit we can set up the initial pulse recurrence frequency of the radar set. By means of suitable clipping devices we can change the waves formed into box-like rectangular pulses. By means of suitable R-C time constant circuits we can then narrow the pulses, determine the slope of the trailing edges, and delay or advance the transmission of the pulses through the circuits. It is our intention to give only a general discussion of resistance-capacitance and resistance-capacitance-inductance circuits.

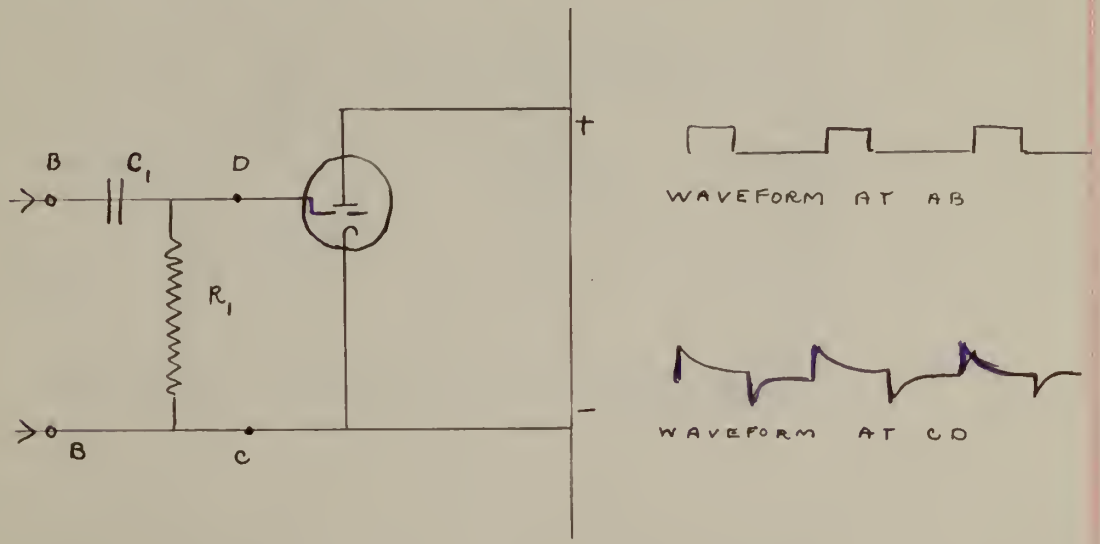
When a capacitor is charged from a direct current source through a series resistance, the charge increases exponentially according to the equation

$$E_c = E\,(1 - \varepsilon^{-t/RC})$$

where E_c is the instantaneous voltage across the condenser C; E is the applied direct voltage in volts across the condenser at time T; ε is the base of natural logarithms; R is the series resistance in ohms; C is the capacitance of the condenser measured in farads; and t is the

instantaneous time in seconds since the voltage was applied. The voltage across the series resistor can also be represented in exponential form, and is equal to $E_R = \mathcal{E} \varepsilon^{-t/RC}$ where E_R is equal to the instantaneous voltage across the series resistor, all other symbols have the same meaning as before. As may be seen from the formulas given, the smaller the values of R and C, the shorter the time required to build up an appreciable voltage across the capacitance. In any specific circuit where there is only one capacitance and any number of series resistances, the R-C value is a constant, usually noted as T, called the time constant of the circuit. The time constant for charge and discharge of the capacitance will be different only if one of the series resistances in the circuit is the dynamic plate resistance of the tube which is cut off during part of the operation.

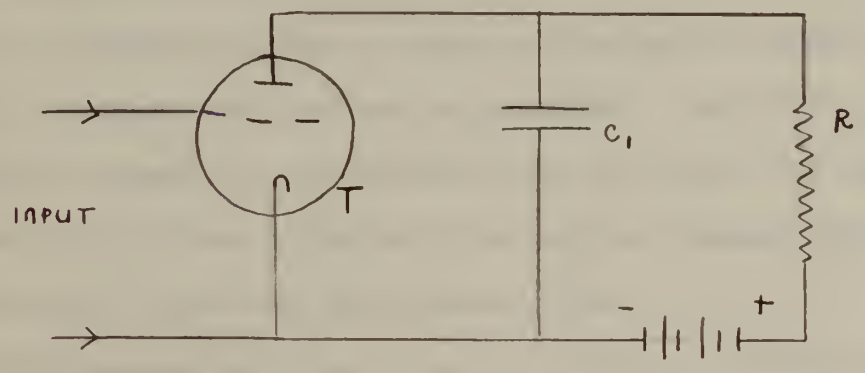
The simplest type of short-time constant R-C circuits useful in producing sharp pulses is shown as Fig. 7.



(Fig. 7). Short Time Constant (R-C) Circuit

This type of circuit is frequently called a differentiator circuit, and it is useful in producing sharp peaked pulses from rectangular waves. The rectangular input wave when applied to the condenser and the series resistance C_1 and R_1 makes them behave as though they had been connected to a source of direct current. The grid bias which is determined by the voltage across the resistance R_1 is at first highly positive. Then, as a charge exponentially builds up across the condenser, the grid potential drops. When the rectangular input pulse cuts off, the condenser discharges through the resistance, and the grid bias becomes slightly negative. The pulse can be applied then to as many amplifying stages as are necessary to give the proper strength.

Another type of R-C time-constant circuits commonly found in a radar set (particularly in connection with the range indicator) is the saw-tooth generator (Fig. 8).



(Fig. 8). Saw-tooth wave generator. Output taken across the condenser C_1.

The circuit is normally operated without grid bias, and consequently a small current flows through the triode T. When a sufficiently negative pulse is applied to the grid to drive below the tube's cut-off point, the tube acts as an open circuit, and condenser C_1 commences to charge through the resistance R. The condenser will charge at an almost linear rate until the negative pulse on the grid is removed, providing the time interval during which the condenser is allowed to charge is only a small fraction of the time required for the condenser to charge to the full supply voltage value. It is important in the operation of the saw-tooth generator that sufficient time be allowed for the condenser C_1 to discharge completely before the grid is driven below cut-off onthe second cycle. Because the condenser can discharge through the dynamic plate resistance of the tube, as well as through the much higher load resistance R, the time constant for discharge will generally be much smaller than the time constant for charge, and a complete discharge is readily obtained.

With these two basic R-C time constant circuits in mind, it is now possible to discuss the means by which the frequency of oscillation of the basic oscillator circuits can be controlled. The blocking oscillator, for example, depends for its operation upon the flow of the grid current. When the grid is driven highly positive, and the secondary emission occurs from the plate of the tube, grid current flows.

The electrons collected by the grid during this period are held by a condenser in the grid circuit. When the condenser has built up enough negative charge, the grid bias will cause the tube to become nonconducting. Then the charge cannot be returned to the cathode directly; instead of returning to the cathode, the charge will leak well away from the

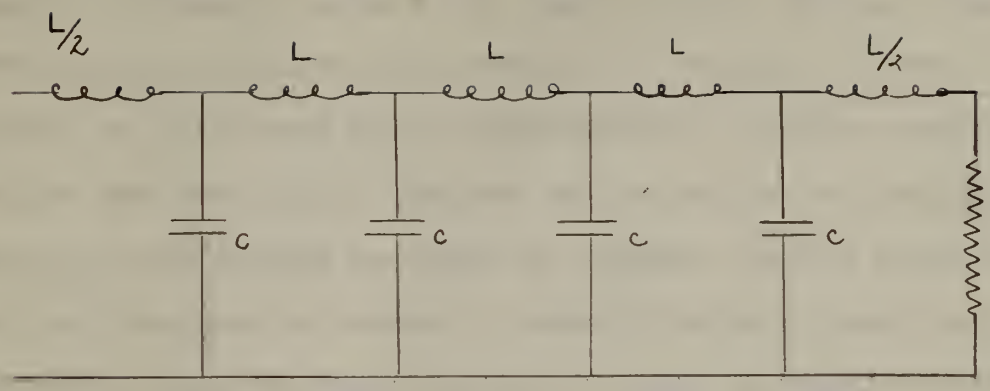
condenser through a resistance. When the charge becomes small enough, the tube resumes operation. The capacitance and the resistance values chosen for these two circuit elements will determine the repetition frequency.

It is not necessary for the timing control circuits to involve only resistances and capacitances. It is entirely possible to make use of the third circuit parameter, which is inductance. Before leaving the R-C circuits we will indicate a few of the difficulties involved in circuit calculations and in circuit analysis.

Perhaps the most significant errors in calculating the performance of short-time constant circuits are introduced by wiring capacitances and internal capacitances of the tube elements. The net effect of these elements in timing circuits is "to round off sharp corners of pulses, to delay steep waveforms slightly and to broaden very narrow pulses and reduce their amplitude."[6] Pentodes are frequently used in timing circuits to avoid grid-to-plate capacitances, and the wiring and the circuit elements must be carefully watched to prevent undue capacitances being introduced. The current voltage relationships, where two or more sets of R-C exponential functions exist, may often be quite complicated and involved. Moreover, in all circuit calculations of this nature, great care must be taken in setting up equivalent circuits, for frequently currents and voltages which are involved in these equivalent circuits cannot be measured, and actually do not exist.

The principal use of inductance in timing circuits is in the pulse shaping line, (Fig. 9), composed of a number of indicators which are

6. Godfrey T. Coate, Principles of Radar, p.2-40.



(Fig. 9). Pulse shaping line in T-Sections.

connected in a series and shunted by condensers. The purpose of the line is to modify pulses impressed upon it in various ways, that are determined by the electrical characteristics of the line itself. The pulse shaping line is frequently called an artificial transmission line, since the inductances and the shunting capacitances are designed to have the same effect upon the impressed voltage as a long length of wire. The network is obviously suitable to act as a delaying device and thus control the sequence in radar operation. The timing delay caused by artificial transmission lines would be the time required for the impressed wave to travel through the network and back. It is desirable to have these artificial networks since an actual transmission line required to delay a wave one microsecond would have to be approximately a 1000 feet long. The artificial network is most effective when the delay required is approximately one or two microseconds.

Artificial transmission lines are also effective in forming square or rectangular waves out of sharp impressed voltage pulses. A voltage pulse applied to input terminals of this type of network travels through the inductances and the capacitances at a finite velocity - the voltage wave being able to progress only as fast as the line will carry to charge, and thus produce the change in voltage. The wave reflected back to the input terminals is reversed in polarity and is a square wave "whose duration is twice the time taken for the energy to travel from the input terminals to the short circuited end of the line."[7]

Inductances are frequently used in conjunction with condensers in other ways, in timing circuits. Many blocking oscillators depend upon pulse transformer or inductive action for feedback to the grid. Certain types of radar sets use L-C circuits in the cathode circuit to give the L-C circuit oscillation when the tube is not operating. These oscillations being of almost constant amplitude, are picked off for use in range measurement.

The purpose of this section has been to give a general picture of a timing circuit, and indicate how sharp trigger pulses may be produced. This section gives the foundation for further discussion; in later sections timing circuits will be specifically applied to their use in the individual sections of a radar set.

7. Jordan McQuay, "Practical Radar," Radio News, m (July, 1945), p.144.

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7. [illegible], "[illegible]," [illegible], [illegible], [illegible].

ULTRA HIGH FREQUENCY OSCILLATORS

Generating Ultra High Frequency Waves

The basic source of the ultra high frequency electromagnetic waves transmitted by a radar set is generally either a triode or a resonant-cavity magnetron. Since the triode's ability to operate efficiently at ultra high frequency levels is limited by factors inherent in the tube itself, the triode has been largely replaced by the resonant-cavity magnetron as the basic source of ultra high frequency energy.

For the reason given above, the principal emphasis of the discussion of ultra high frequency generators will be placed upon the resonant-cavity magnetron. However, a limited summary of the methods by which triodes may be used will be given first, and will serve to introduce the discussion of problems encountered in generating ultra high frequency waves.

(A) Triode Oscillators

To increase the natural frequency of oscillation of a circuit containing both inductance and capacitance, we must decrease either the inductance of the circuit or the capacitance of the circuit, or both. The criterion for such a statement follows directly from the fact that the natural frequency of oscillation of such a circuit is inversely proportional to the square root of the total inductance and capacitance of the circuit. In the final analysis, the limit of one's ability to reduce the inductances and the capacitances of the circuit is fixed by the inductance and capacitance associated with the lead wiring and tube elements.

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It was found that, in general, the efficiency and power output of the normal triode fell off quite rapidly in the region of 50-60 megacycles per second, and if attempts were made to increase the frequency much beyond this limit oscillations ceased entirely.

The principal cause for the loss of efficiency and power output at high frequencies is the time required for electrons to travel from cathode to plate. "In tubes of conventional structure the transit time may be of the order of magnitude of 0.001 microseconds."[8] At audio-frequencies this transit time is still relatively unimportant. However, as one approaches the high radio frequencies and the ultra high frequencies the transit time cannot be ignored, for it then becomes comparable to the period of the wave generated. The net effect of transit time at high frequencies is to increase the input conductance of the tube and to reduce the output efficiency.

There are two other principal causes of high power loss and consequent low efficiency at ultra high frequency levels of operation. The first cause is that substances which act like dielectrics at low frequencies may prove ineffective in the ultra high frequency region. The second cause is that every section of the circuit involved in ultra high frequency generation behaves, in effect, as though it were part of the transmission system, and then consequent radiation losses may be quite high.

Since all the factors mentioned above, that limit the oscillations at high frequences, involve the physical dimensions of the triode and

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8. J. G. Brainerd, Ultra High Frequency Techniques, p. 297.

its associated oscillatory circuit, there are many ways by which the triode's performance can be greatly improved. Lead inductances may be minimized by using very short leads; interelectrode capacitances may be minimized by making electrodes small. The time required for the transmission of electrons from cathode to plate may be reduced considerably by applying high plate voltage, and by moving the plate and the cathode closer together. (The latter method of shortening transit time is always a compromise position, for moving the plate and the cathode close together results in higher interelectrode capacitance). Radiation losses may be largely eliminated by making circuit elements short, and by using concentric transmission lines. Dielectric losses may be minimized by eliminating the tube base altogether, and by making lead connections directly to the electrodes through predetermined points in the glass bulb.

The "acorn" tube and the "door-knob" tube are diminished tubes specifically designed to generate ultra high frequencies of 40-50 centimeters wave length, but neither is designed to generate the high power required for the transmission signals. Perhaps the most satisfactory triode devised to generate ultra high frequency waves to use in the radar set is the lighthouse tube (G L 464) which can be used to generate waves of approximately 30 centimeters wave length at peak power levels of one kilowatt.

The oscillatory circuits in which triodes are used are the negative-grid oscillatory type used in the Colpitts, tuned-grid tuned-plate or tuned-grid, tuned-cathode circuits. The principal modification of these circuits is the removal of the tuning device consisting of an

inductance and a capacitance, and the replacing of the tuning device with some type of Lechner wire system or concentric line "stub."

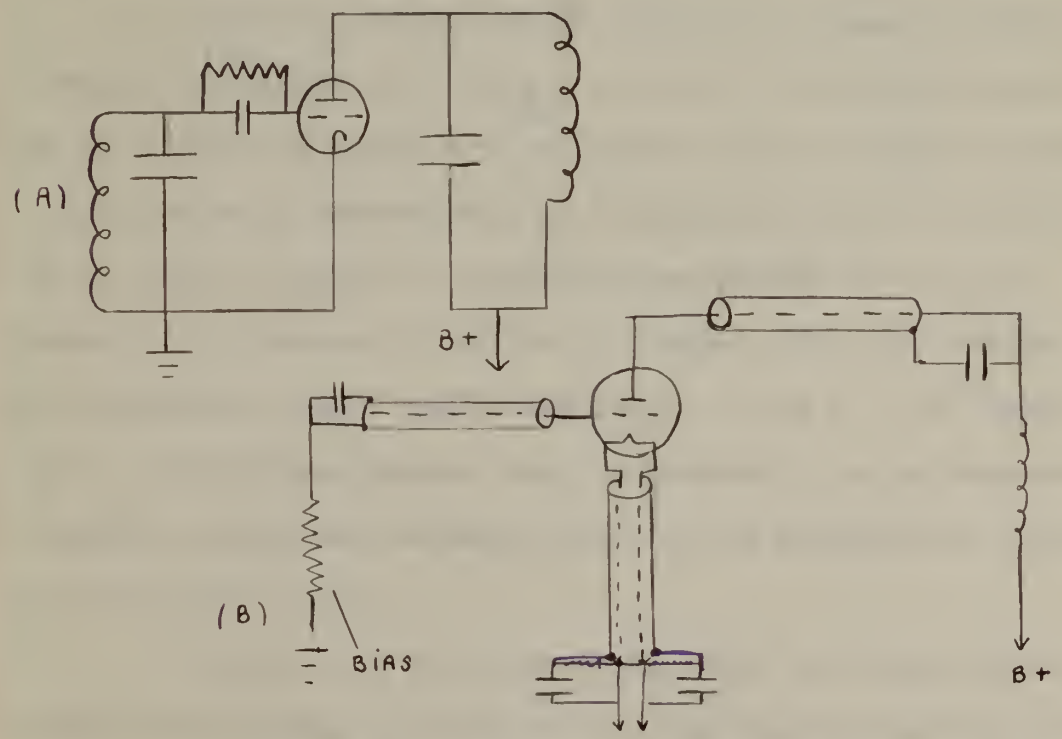
Since the peak power of the radar transmission has to be extremely high, one triode is usually not enough to generate the ultra high frequency needed. Therefore it is quite common for two tubes or any number of pairs of tubes to be connected in series push-pull. The easiest way to arrange more than one pair of tubes together is around the circumference of a circle. Circuits of this type, known as ring type oscillators, are widely used.

There are other methods of connecting tubes or sections of the same tube. The A N /TPS-3 radar set which operates at a frequency of 600 megacycles per second has as its source of ultra high frequency power a single tube consisting of four triode sections, connected in push-pull parallel fashion and dependent for its oscillation upon tuned-grid tuned-plate action. The tube specifically designed for radar work has a relatively long transit time requirement, and will operate efficiently only after the applied voltage exceeds 5,000 volts. The average peak power output of the set is about 200 kilowatts, with an average output power level of 60 watts.

A figure indicating the main differences between an oscillator circuit designed for the audio frequency range, and one designed to generate ultra high frequency waves are shown as Fig. 10.

Before entering into a discussion of the magnetron it may be well to clarify the meaning of peak power and average power when referring to radar equipment specifications or characteristics. The peak power of a radar set is the maximum power of the set when a pulse

is being radiated. Generally it may be calculated as the product of the modulating voltage, the maximum anode current, and the plate efficiency of the ultra high frequency generating device. The average power output of a radar set has little meaning unless further details on its operation are given; the average output power will depend principally upon the duration of the quiescent period, and will decrease rapidly as the quiescent period becomes longer. The peak power of the set will be governed by the ability of the ultra high frequency generating device to withstand high peak current-voltage values, and by the ability of the cathode to emit sufficient electrons to give large current. In general, the size of the tube can be reduced with lower value of average power.



(Fig. 10). Tuned-grid tuned-plate Circuit. (A) Equivalent circuit using concentric lines. (B)

(B) Magnetron

The most practical source of ultra high frequency energy of high peak power is the resonant-cavity magnetron. Where the triode's ability to generate ultra high frequency energy is limited by the transit time required for an electron to pass from cathode to plate, the resonant-cavity magnetron utilizes the transit time and consequently is highly efficient even at wave lengths close to 1-2 centimeters.

The magnetron tube is a diode whose electrostatic field is cut by a magnetic field. The electrons released by the cathode and into a magnetron tube are immediately subject to two different forms, (1) the field strength of the electrostatic field of the diode and (2) the magnetic flux.

The force exerted upon an electron by a magnetic field is given by the expression $F = \frac{B\ e\ v}{10}$, where F is the force exerted on the electron in dynes, B is the magnetic field strength in gausses, v is the velocity perpendicular to the magnetic field of the electron as it enters the field, in centimeters per second, and e is the charge on the electron in electrostatic units. The force exerted by an electrostatic field upon an electron is $F = E\ e \times 10^{7}$ where F is the force in dynes exerted upon the electron, E is the electric field strength in volts per centimeter, and e is the charge on the electron in electrostatic units.

The effect of the electrostatic field upon the electron is purely translational, and tends to pull the electron from the cathode to the plate. The effect of the magnetic field on the electron is to make the electron execute a circle. If the electrostatic and magnetic fields are both applied at once and are mutually perpendicular, the path

of an electron in the field will be some form of cycloid - the particular path being determined by the relative field strengths and the initial velocity.

The principle of the magnetron was discovered by Hull in 1921. The tube with which he experimented was not essentially different in principle from the tube used in the resonant - cavity magnetron of today. It was a diode consisting of a cylindrical anode and a coaxial cathode. The magnetic field was applied parallel to the axis of the cathode, and therefore perpendicular to the electrostatic field. When plate voltage was applied to the diode, plate current flowed through the tube. When there was no magnetic field impressed upon the diode, the electrons emitted by the cathode traveled directly to the plate under the influence of the electrostatic field. When a small magnetic field strength was applied, the electrons emitted by the cathode were subject to two forces acting at right angles to one another, and the subsequent electron path was a curve whose sharpness depended upon the relative strengths of the two forces applied. Under these conditions the electron's path from cathode to plate was curved, but plate current still flowed. As the magnetic field strength was increased, the force exerted by the electrostatic field upon the electrons emitted by the cathode was eventually completely counterbalanced by the force of the magnetic field. The path of the electron was a closed loop beginning at the cathode and terminating at the cathode, as shown in Fig. 11c. Under these conditions no plate current flowed. If the magnetic strength was increased beyond this critical or cut-off value, the electrons could be made to complete several spiral curves before returning again to the cathode. By maintaining the magnetic field strength just above its critical value, the

tion in

electrons could be made to leave the cathode and graze the plate, without actually being absorbed therein, and then return to the cathode. The combined effect of many electrons traveling the same type of path resulted in an ideal method for sustained oscillations. Four illustrations of the path of the electron under different magnetic field strengths are shown as Fig, 11.

(Fig. 11). Electron paths in static electric and magnetic fields.

Later experimenters split the cylindrical anode of Hull's tube into sections, along the length of the cylinder, until the cylinder became nothing more than numerous and very narrow strips of metal arranged in circular fashion about the cathode. Most of the tubes designed on this principle were capable of generating ultra high frequency waves of short wavelength, but none would give the high peak power levels required for use in radar.

The British under the pressure of war, adapted the magnetron to ultra high frequency generation uses by combining the principles of the resonant-cavity chamber with the magnetic-electrostatic diode of the magnetron. This resulted in tubes that were capable of generating up to eight million watts at wavelengths of 25-30 centimeters, and

over 1/2 million watts at wave lengths as low as 1-2 centimeters. Moreover, experimental tubes operating at 10 cm., have developed a peak power level of 4,000,000 watts.

The resonant-cavity magnetron is similar to the magnetron in appearance. It is a diode which maintains control over the cathode-emitted electrons by using a magnetic field parallel to the axis of the tube. The anode designed to make use of resonant-cavity principles is a heavy cylinder, usually of copper, around whose inner circumference are a series of identical chambers, each connected to the center of the cylinder by a narrow open slot. The chambers are specifically designed to resonate at the output frequency desired, and are spaced so that adjacent chambers or cavities oscillate in reverse phase.

The cathode is at the center of the cylinder and is generally a nickel sleeve, coated with some active material from which a copious flow of electrons can be obtained. The power output is removed by means of a coupling loop contained in one of the resonating chambers.

The anode of the tube is normally grounded for reasons of safety, and oscillations start when an extremely negative modulating pulse is applied to the grid. The electrons emitted by the cathode are whirled past the resonant-cavities by the combined electrostatic and magnetic forces, and the net result is to set up extremely high-powered oscillations in the resonating chambers. In order that unwanted frequencies be eliminated from the output of such a magnetron, it is important that the modulating pulse be as nearly rectangular as possible. Further discussion of the modulating process will be given in the next major section.

The magnetic field associated with the magnetron is generally created by a permanent magnet although electromagnets are also used. In many sets

the magnet is a permanent part of the structure of the radar set, placed there when the set is constructed. The magnetron tube itself is then placed between the two poles when the set is ready to operate. In many similar portable sets, the magnet and magnetron tubes are permanently attached to one another.

The most important requirement of the magnet when used with a magnetron is that it maintain a constant field strength. "Variations in the magnetic field are to be avoided since they introduce simultaneously variations in output power, operating efficiency, and output frequency."[9] The strength of the magnetic field required will vary with the radar set. The sets requiring high peak power will generally require high magnetic field strengths togo with high modulating voltages.

The frequency of the magnetron output is largely determined by the original size of the resonant-cavities of the anode. Slight adjustments in resonating frequency can be made in some radar sets by moving the top or the bottom of the chamber of the diode. Thus by changing the dimensions of the resonating cavity, we change its resonating frequency. The output of the magnetron can usually be adjusted by suitably varying theoutput impedance.

The resonant-cavity magnetron rarely operates at an efficiency higher than 35-37 per cent, and generally it will oscillate at a definite fixed frequency. Great care should be taken so that the cavity-magnetron in the radar set will not be operated without a magnetic field. Excessive current may flow and do considerable damage to the magnetron and the source of

9. "Cavity Magnetron," Electronics, (January, 1946), p.130.

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The resonant-cavity magnetron rarely operates at an efficiency higher than 25-37 per cent, and generally it will oscillate at a definite fixed frequency. Great care should be taken so that the cavity-magnetron in the radar set will not be operated without a magnetic field. Otherwise current may flow and do considerable damage to the magnetron and the source of

7. "Cavity Magnetron," Electronics, (January, 1946), p.130.

modulating voltage. The principal sources of irregularities in output frequency and power levels are in the anode current and in the low applied voltage. Most magnetrons are designed to be used at power levels of 500 kilowatts.

The peak power output of the magnetron is limited by the resistance of the internal structure to sparking, and by the ability of the cathode to produce sufficient electrons during the brief oscillating period.

Transmission Of Ultra High Frequency Waves - Wave Guides And Coaxial Lines

The transfer of audio-frequency electrical energy from one point to another is commonly done by means of transmission wires. However, as the frequency of the transmitted energy becomes greater, new methods have to be devised to compensate for, and minimize power losses due to radiation and heating effects. Both the radiation and the heating losses increase with increased frequency.

At the high radio frequency and ultra high radio frequency levels used in radar work, electromagnetic energy is commonly carried from one portion of the set to another by means of coaxial cables or hollow wave guides. Hollow wave guides are of no practical importance unless the wave length of the electromagnetic energy being transferred is less than 10 centimeters. At wave lengths greater than 10 centimeters, the coaxial cable is used as the carrier.

The coaxial cable, as the name implies, consists of a comparatively small wire completely surrounded by a much larger cylindrical conductor. The inner wire is held at the axis of the outer cable by some type of insulating material, quite commonly polystyrene. The insulating material may

modulating voltage. The principal source of irregularities in output frequency and power levels are in the anode current and in the low applied voltage. Most magnetrons are designed to be used at power levels of 5% allowable.

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support the wire at strategic points or be a continuous sheet between the inner conductor and the outer cable. The former method, called beaded insulation, is widely used and results in smaller dielectric losses than the continuous type.

It is possible to have quarter-wave length short-circuited stubs act as supports for the inner wire if the electronmagnetic wave length is less than 10 centimeters. However, the size of the stub required becomes prohibitive at longer wave lengths.

The current flow in a coaxial cable takes place along the outer surface of the small inner conductor and along the inner surface of the outer conductor. Consequently the radiation losses are very small. The attenuation of the cable is minimized by making the radius of the inner surface of the outer conductor 3-4 times as large as the radius of the inner wire. In practice this ratio may vary from 2.5 to 7.0. Since the coaxial cable can be constructed as either a flexible line or a rigid cable, it is ideally suited for use in radar equipment.

At the extreme ultra high frequencies, beyond 3,000 megacycles per second, a hollow pipe or tube may be used instead of the coaxial cable and the electromagnetic energy can be guided between one section of the set and another, instead of flowing through a carrier wire. The hollow tube has several advantages over the coaxial line. One of the major problems required in designing a coaxial cable is in providing the central wire with relatively strong mechanical supports that will not interfere with the electrical properties of the cable. The design of the hollow tube involves no such problem.

The dielectric losses in the hollow wave guide are even smaller than those in the coaxial cable. Moreover, removal of the central wire eliminates a major portion of the conductive heating losses, for skim-effect losses of

of this nature vary inversely as the perimeter of the cross-section of the conductor. The power carrying ability of the hollow tube is greater than the coaxial cable of the same size.

The principal limitation placed upon the wave guide is that its largest dimension must be equal to or greater than one-half the wave length of the electromagnetic energy which it passes. This limitation is unimportant at wave lengths of 10 centimeters or less, as compared with the advantages of the wave guide previously given. But it would take a tube over 50 centimeters wide to pass electromagnetic waves of one meter wave length.

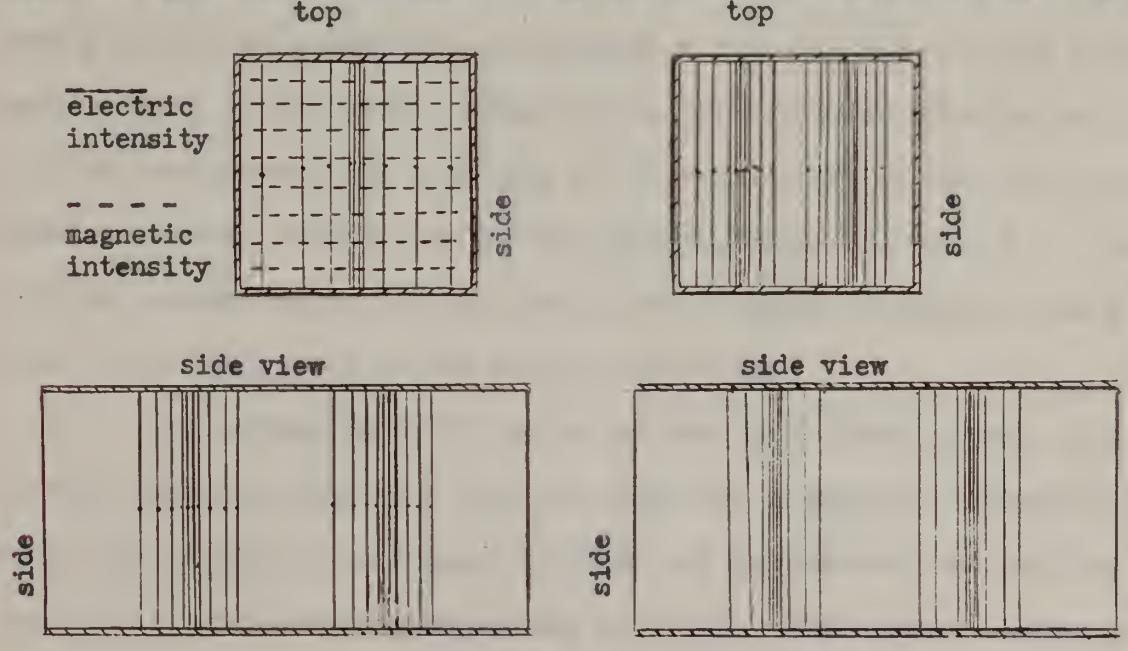
The rectangle is the most important shape for practical use in the construction of wave guides. Circular wave guides can be used at joints and elbows, and they are desirable for mechanical reasons. However, use of the circular wave guide is avoided wherever possible because the frequency range between cut-off for the desired frequency and cut-off for higher undesired frequencies is very narrow. Moreover, any ellipticity of the tube is liable to elliptically polarize the electromagnetic energy being carried, and make it difficult to handle at the output.

As previously mentioned, the largest dimension of rectangular wave guides must be at least one-half as large as the wave length of the electromagnetic energy being carried. The smaller dimension is generally smaller than one-half wave length, although there is no exact specification. If just below one-half wave length, the smaller dimension minimizes the attentuation of the hollow tube.

In the ultra high frequency region where wave guides may be used, discussions of voltage and current relationships have little meaning; it is

better to deal with electric and magnetic field intensities. If the size of the hollow wave guide is known, it is possible to determine exactly what types of magnetic and electric fields can be established by electromagnetic energy passing through. These possible configurations are called modes. There is usually more than one mode associated with each tube, and a system has been devised to refer to the basic types. A figure illustrating possible configurations in a rectangular wave guide is shown as Fig. 12.

The notation used will not be dealt with in detail since it is relatively unimportant. However, the modes are classified according to whether the electrical or the magnetic field has a component in the direction of propogation of the energy. The T E (transverse electric) mode has a component of the magnetic field intensity in the direction of propogation, but it has no electrical component . The T M (transverse magnetic) mode has a component of the electrical intensity in the direction



(Fig. 12). Field configurations in a rectangular hollow wave guide.

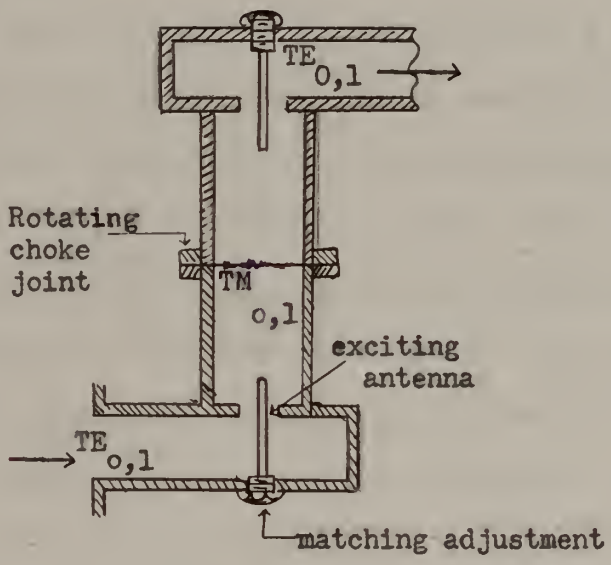
of propogation but it has no magnetic component. To further identify the type of mode present, it has been found convenient to add a double subscript to the T M or T E notation. Thus $T E_{1,0}$ stands for a transverse electric mode in which one-half a sinuoid wave is encountered through one dimension of the rectangular tube, and no sinuoid wave is encountered through the other dimension. Slight adaptations can be made on this notation system to describe the modes present in a circular wave guide. The $T E_{0,0}$ mode is not possible, neither are the $T M_{0,1}$ or $T M_{1,0}$ configurations. All other modes of higher order are theoretically possible.

Abrupt turns are not always possible with either the coaxial cable or the hollow wave guide, but in general, the efficiency of transfer of electromagnetic energy is not greatly effected by a gradual shift in direction.

There are various ways by which the coaxial cable and the hollow wave guide may be connected to an antenna so that the line or wave guide need not move as the antenna scans the surrounding area. The coaxial cable at 25-50 centimeters uses some type of rubbing contact at the joint between two wires. However, as the wave length becomes shorter, it is possible to adopt another method called capacitative coupling to transfer energy from a stationary cable to one which is rotating.

The methods by which the hollow wave guide feeds energy into a rotating antenna system vary from one radar set to another. Generally the wave guide itself is rectangular in shape and the dominant mode of the rectangular pipe must be changed into a circular mode at the rotating joint. It may again be changed back into a rectangular mode before actually reaching the antenna system. One method of transferring the input $T E_{0,1}$

mode into a circular $TM_{0,1}$ mode in a rotating antennajoint, and back again in the $TE_{0,1}$ mode, is shown in Fig. 13. Since the electrical and magnetic fields of the circular pipe are symmetrically about the axis of the small exciting antenna, the rotating effect does not result in eliptically polarizing the input.



(Fig. 13). Rotating antenna joint

TRANSMITTER

Modulator

The preceding section has been principally concerned with how ultra high frequency waves may be generated. Also how these waves may be transferred from one part of the set to another. However, it is important to realize that a continuous stream of ultra high frequency energy is not required in radar work.

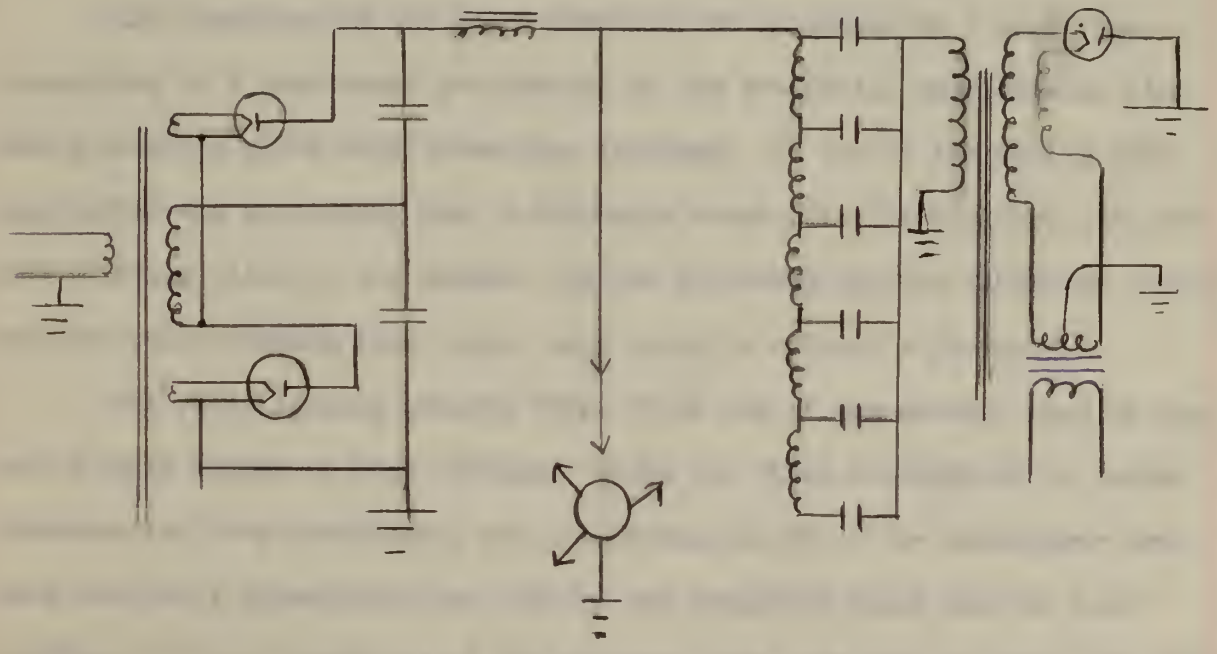
Energy from a radar transmitter is not emitted in a continuous stream, but in pulses of short duration. These pulses constitute only a fractional part of the total duty cycle of the radar; during the remainder of the duty cycle, the radar set listens for returned energy. Thus, for example, the duration of the output pulse may be only one microsecond, while the period of silent listening may be over 1000 microseconds. The process by which pulses of ultra high energy are formed is called modulation.

The obvious source of modulating power is the basic timing-control circuit. However, the power generated in the timing-control circuit of a radar set is generally very small, and a voltage wave obtained from this source would be of insufficient strength to start oscillations in the ultra high frequency generator. As a result it is usually necessary to have a separate circuit form the required voltage modulating pulse.

The principal requirement of the modulating pulse is that it be as nearly rectangular as possible. The leading edge of modulating voltage must be sharp, in order to prevent unwanted and unstable oscillions being set up in the ultra high frequency oscillator. The modulating voltage must have a constant peak value during the major portion of the modulating period for unstability in both frequency and power outputs will result if the

modulating voltage varies. The length of the period of the modulating voltage and the sharpness of its trailing edge are important only in determining the minimum range of the set, for any echoes received from nearby objects while energy is being radiated, will pass undetected by the listening device.

The rectangular modulating voltage may be either a highly positive or a highly negative pulse. A highly positive pulse applied to the grid circuit of a triode, normally biased below cut-off, can raise the grid potential high enough to start sustained oscillations. The same type of pulse applied to the plate circuit of the triode or the magnetron can bring the plate potential up to a value suitable for sustained oscillations, if the other circuit elements are satisfactory. A highly negative pulse applied to the cathode circuit can be made to satisfy conditions necessary to start oscillations.



(Fig. 14). Radio-frequency modulation.

Fig. 14 illustrates one method by which the modulating voltage may be obtained, and also shows how the modulating voltage can be applied to the R-F oscillator.

The modulating system consists of a voltage-doubling circuit, a charging choke or filter, and an artificial transmission line. The sine wave input is applied to the two rectifying diodes which charge through their associated condensers in such a way that one voltage adds to the other. The output is then passed through a smoothing choke to the artificial transmission line which builds up a charge quite slowly to a high value, and then discharges to the ground. The discharge of the line applies a strong pulse to the primary of the transformer which connects the pulse forming line with the radio frequency oscillator. The transformer, a step-up voltage transformer, may increase the voltage value 3-4 times before applying the pulse to the radio frequency oscillator.

The discharge of the pulse forming line is caused by a spark gap, consisting of a stationary pin charged by the artificial transmission line and a rotating plate with three pins attached. As one of the moving pins approached the stationary pin, a discharge takes place through the pin, and the rotating plate to the ground. As the pin moves by, the discharge ceases, and the pulse forming line begins once again to collect a charge.

The pulse forming network (Fig. 9) is one of the methods used to generate sharp pulses of high voltage. There are other networks which employ transmission line techniques, and the determination of the particular network used will depend upon how rigidly the modulator pulse must be controlled. If the circuit is of the open-end type, the time required for the discharge of the line is a function of the capacitance and the resistance. If the circuit is of the short-ended type, the time required for discharge is

a function of the inductance and the resistance.

The effective use of the charging line generally depends upon a switching device which is open while the line charges, and is closed when the pulse is allowed to pass to the ultra high frequency oscillator. The device may be a spark-gap switch as shown in Fig. 14, or it may be a saturable coil reactor. The principal requirement of the switch is that it must allow the charging line time to build up an appreciable charge before releasing the pulse to the oscillator.

The power or voltage of a pulse produced by a charging line, or by other means, can be readily amplified in this stage since radio frequencies are not present. However, the amplifier tubes must be designed to handle high values of voltage and of current. There may be as many stages of amplification as desired; the tubes used being class A or class A-B distortionless amplifiers, coupled by resistance-capacitance circuits.

Only one more detail need be mentioned in connection with the modulator. The duration of the modulating pulse will determine to a large degree the quality of the high frequency response necessary in the receiver. The shorter the pulse duration, the better the high frequency response of the receiver must be to retain the correct over-all envelope of the returned energy.

Antenna

The primary purpose of the transmitting antenna system is to t[illegible] radiate into space efficiently and with high directivity beams of electromagnetic energy. The advantages of high efficiency in operation are obvious and need no explanation. The advantages of high directivity are equally important, if not as obvious.

Antenna

The primary purpose of the transmitting antenna system is to radiate into space efficiently and with high directivity power of electromagnetic energy. The advantages of high efficiency in conversion are too obvious and need no explanation. The advantages of high directivity are equally important, if not as obvious.

The three principal advantages of a highly directive radar beam are: (1) the power of the radiated energy can be most effectively utilized by concentrating the energy into a single narrow beam; (2) the direction from which the target echo is received can be most accurately determined if the radiated beam is highly directive; (3) two objects very close together can be recognized as separate distinct objects only if the radiated beam is narrow.

There is one limiting factor to the desirability of narrowing the beam. The ability of the radar set to scan a large area in brief intervals of time is seriously impaired if the beam radiated is too narrow.

Antennas are used to transmit electromagnetic energy and to receive reflected energy. In most radar sets, although not all, a single antenna system is used to radiate energy and to receive energy. As a result, the principles established for the transmitting antenna are also adaptable to the receiving antenna.

Radiation of electromagnetic energy from antenna systems is not a new concept and many of the antennas used in radar equipment are quite similar in operation to those used in radio and communication apparatus of the past. However, the handling and the directing of microwaves or waves a few centimeters in wavelength has brought with it new methods and equipment.

The basic method through which electromagnetic energy may be radiated is in the use of one or more dipole antennas. The dipole is a cylindrical rod of conducting material, approximately one-half wavelength long. Energy supplied to the conductor results in a fluctuating electric and magnetic field being set up around the dipole. The charge on the dipole

fluctuates with the voltage applied, in such a manner that the extreme ends of the dipole always have zero current and maximum voltage, and the center of the dipole will have maximum current and zero voltage.

The electric and magnetic fields set up by the oscillations of electromagnetic energy in the dipole consist partially of inductive energy and partially of radiated energy, i.e. energy which continues outward away from the dipole. While the inductive energy field is highly important in determining the action of the dipole as a circuit element, the radiated energy field contains the propogated energy and determines the directional characteristics of the beam.

The resistance and reactance of any radiating antenna varies with the length of the antenna. When the antenna is of resonant length slightly shorter than $\lambda/2$, λ, ..., the reactive power required is zero and the antenna acts as a pure resistance. If the antenna is not of resonant length, it will present capacitative or inductive reactance. The resonating length varies with the diameter of the rod used, and it decreases as the rod diameter increases.

The radiations issuing from a single antenna have little directivity. The radiations expand radially outward with the maximum flux intensity being at right angles to the length of the antenna and falling off to zero along the axis of the antenna; therefore, the single antenna has little use in radar wave propogation.

When two or more dipoles are used together, the radiation pattern is the result of the individual antennas; higher directivity can then be obtained. Large combinations of dipoles are commonly called arrays and are highly important, particularly in early radar sets.

Arrays of dipoles are usually connected in regular geometrical patterns, but unsymmetrical arrangements are sometimes used. The ultra high frequency voltage waves may be applied to the dipoles either in phase or out of phase, depending upon the pattern desired.

One of the principal ways that two antennas may be used to create a directional pattern is in the connection of one antenna to the driving power, with the other antenna used as a reflector. The reflector is a dipole usually slightly longer than one-half wave length. It is placed one-quarter of a wave length behind the antenna which is being driven by the external source of energy. The radiating field of the first antenna activates the second antenna and the net result is the strengthening of the radiation field away from the reflector through the first dipole. This method of obtaining directional radiation is used in certain types of coastal defense radar sets. It directs energy which is fed from the ultra high frequency source against a reflector, and the principles involved have been adapted to many other antenna arrays.

One of the principal uses of an array of dipoles is in the broadside array. This type of array sends out the major portion of its radiated energy in a direction perpendicular to the plane which contains the radiating antennas. The array usually consists of two or more dipoles connected in parallel and fed in phase.

When measuring the directivity with which the antenna array radiates energy, we are concerned with the amount of energy being radiated in a single direction. The beam angle is defined as the angle between half-power points. The beam angle of a broadside array can be shown to be inversely proportional to the number of dipoles in the array and to the spacing between these dipoles

in wavelengths.

Arrays of dipoles have been widely used in radar equipment, the number of dipoles used varying greatly. Thus, the SCR-545 used in directing anti-aircraft fire had sixteen dipoles, arranged in four symmetrical arrays, direct a beam of ultra high frequency energy against a reflector, while the AN/APQ-7 antennas used in the Army's B-29 had an array of 250 dipoles, spaced half a wavelength apart, as the actual projecting mechanism.

When one arrives at the extremely low wavelengths, it is possible to focus the energy output of the ultra high frequency generator into highly directive beams by means of reflectors or by means of spherical lenses. The principal limitation on the use of reflectors is that their dimensions must be large, as compared with the actual wavelength being reflected. Thus the paraboloid reflector can be effectively used to focus ultra high frequency energy, only if its dimensions are large enough, so that the source of energy can be considered a point source.

Whenever size limitations permit, the parabolic reflecting antenna is generally used, for it forms a highly directive energy beam of high power. There are many different sizes and shapes that the parabolic reflector may take. The paraboloid is a very common shape. Also, the parabolic cylinder is widely used.

Feeding of ultra high frequency to the reflecting surface is done by arranging a small antenna system within the radiating antenna system. Thus in the process already described, a dipole placed at the focus of the parabolic reflector with the parasitic antenna a quarter of a wavelength to the rear can be used to direct a beam of energy upon the surface of the reflector. The reflector reverses the direction of the electromagnetic energy and sends

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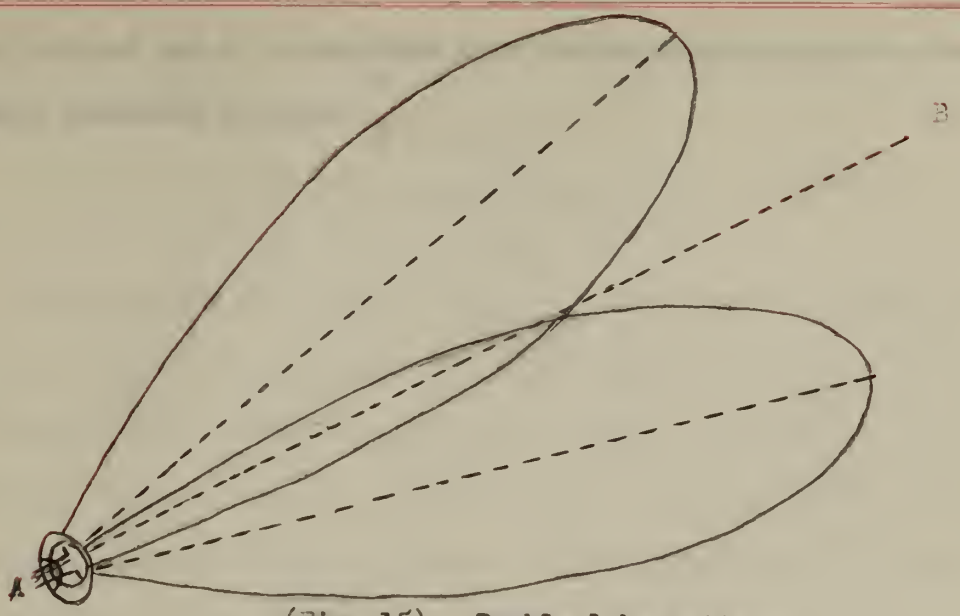
out a narrow beam of highly concentrated energy. In recent years, the parasitic antenna has been commonly replaced by a small flat plate of reflecting material, which directs the energy towards the larger reflector.

If the ultra high frequency energy has been guided to the antenna system by wave guides, the opening at the end of the wave guide can in itself serve as the radiator of the energy against the reflector; however, it is generally desirable to widen the larger dimension of the rectangular wave guide, in order to direct the energy against the reflector effectively.

We shall consider the means by which the physical position of the target is determined. The distance of the target from the observer is a function of the time required for a pulse to leave the antenna, strike the target, rebound, and be received by the observer. The direction of the target may be found by adjusting the rigid antenna system until the strength of the returning energy appears to be a maximum. The object's exact position has been isolated when the distance, the elevation angle, and the azimuth angle have been established. A precise determination of the position of the target requires a highly directive beam.

It is possible to determine even more accurately the position of the target if we use two beams of electromagnetic energy instead of one. The two beams are shown as Fig. 15. They are projected at a slight angle to one another. If an equal amount of energy is returned to the observer for each beam, the target must lie on the line shown as AB in Fig. 15. The ability of the radar set to scan a large area is greatly improved by the use of two beams, and at the same time the accurate determination of the position of the target is greatly improved.

The source of the two beams may be two separate antennas. Generally,



(Fig. 15). Double-lobe pattern.

however, the two beams are formed in a paraboloid or in some type of parabolic reflector by feeding the energy to a reflector from one side of the focal point and then from the other side.

There is another method used to determine the exact location of the target. This method also involves the feeding of energy to the reflector from a point other than focal, and it is called conical scanning. The antenna is usually a paraboloid reflector whose feeding device is rotated in a regular fashion about the focal point. The result is a beam which rotates about a central axis, while the entire antenna system moves up and down or back and forth, scanning the surrounding area.

Great care must be exercised in feeding the energy to a parabolic reflector from any point other than the focal point, for the outgoing beam may be appreciably altered. "The first effect of moving the feed away from the focus in the focal plane of a paraboloid is indeed a beam shift but before this process has gone far a third order curvature of the phase front

is produced and is accompanied by a series deterioration in the pattern and a reduction in gain."[10]

10. H.T. Friis and W.D. Lewis, "Radar Antennas," Bell System Telephone Journal, VOL. xxvi, (April,1947), p. 283.

RECEIVER

Problems in Radar Reception

The receiver in a radar set must be an extremely sensitive hearing device. It must be able to receive input signals that are so often weak that they must be measured in micromicrowatts. The ability of the receiver to detect such weak signals, amplify them, and by suitable means recognize them as reflected energy, determines to a large degree the maximum effective range of the radar set.

Strangely enough it is not the extreme weakness of the returning echo which limits the ability of the receiver to detect the presence of a target. Instead, the limitation is inherent in the receiving system itself, and it is primarily due to random fluctuations in voltage and current between circuit elements. These variations in voltage and in current result in appreciable fluctuations in the output of the receiver, and mask or conceal the weak input echoes from the target.

The fluctuations which conceal the signal input are commonly called noises, and are the result of (1) thermal agitation, (2) shot effect, and (3) the electrostatic and electromagnetic fields associated with the receiving circuit. Since noises due to these factors limit the sensitivity of the receiver, they will be discussed briefly.

The first cause of noise is due to the random motion of electrons flowing through a resistance. The variation in intensity of electron flow introduces a random voltage and current pattern which is carried on through the receiving system as noise. The amount of noise associated with this

effect decreases as the resistance and the temperautre values of the resistor decrease, and the band width of the frequencies being passed decreases.

The second principal cause of noise is due to shot effect within the tubes of the receiver circuit. In any type of tube, irregular emission from the cathode results in irregular plate current, and in appreciable noise voltage being built up across the tube resistance. If there is a negative potential or control grid in the tube, the irregular pattern,in which the electrons pass from cathode to plate current,causes an irregular current flow in the external grid circuit, which in turn results in a noise voltage being applied to the grid. If there is a positive grid in the tube, the electron flow is divided between the two positive electrodes; the net result increases the irregularity with which the electrons arrive at the plate.

The third principal cause of noise in the receiving circuit is a stray electromagnetic or electrostatic field. Noise due to these effects can usually be eliminated by the use of proper shielding devices.

In addition to receiver circuit noises there are some noises actually carried into the receiver from such external sources as noise due to storms; however, the amount of noise introduced into the receiving circuit from external sources is usually small, as compared to noises generated in the circuit itself.

The amount of noise produced in the receiver system itself may be reduced within a few decibels of the theoretical limit, by careful design and construction. Frequently the noise may be greatly reduced merely by physically separating the circuit elements, thus reducing circuit interference. Particular care should be exercised in designing the initial stages of reception to prevent excessive noises being introduced, for any noise

frequencies generated in the first stage will be fed into the amplifying sections where they will be greatly amplified.

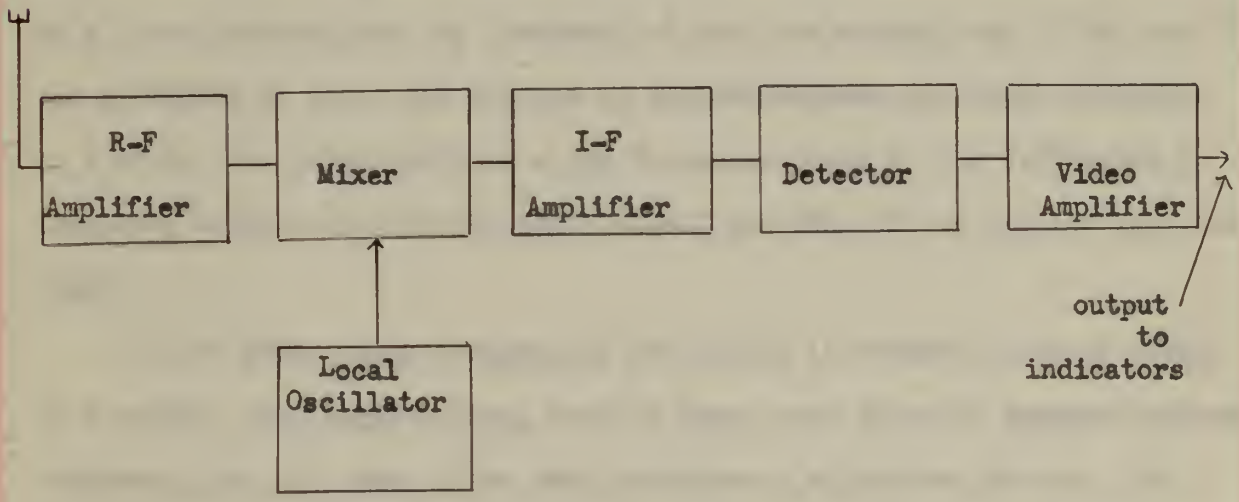
Another big problem in reception is the time taken for the affect of the transmitted pulse on the receiver circuit to leak away. Even the T-R box (discussed at the end of this section), allows a comparatively large amount of energy from the transmitted pulse through to the receiver. The leakage builds up an immediate charge on the coupling condensers in the receiving circuit, and while this charge leaks off of the condensers, the associated tubes may be biased below cut-off.

There are several methods used to aid in eliminating the problem. In the intermediate-frequency amplifying stages when single-tuned coupling is used, the coil is frequently placed between the coupling condenser and the grid. The type of arrangement used allows the blocking voltage to be immediately transferred to the plate circuit where it does little harm. Generally in this section of the receiving circuit, the blocking voltage is small and the recovery time quite short.

Some radar sets use limiters in the receiver to limit the voltage passed through to the parts of the circuit where blocking might take place. The use of the cathode follower as the second and last stage in the video amplification section allows a large swing of grid voltage before grid current flows. Moreover, it is usually possible to have the output of the detector circuit negative. Too large a pulse passed to the grid of the first tube in the video amplification stage can then drive the tube below cut-off before the grid of the following tube draws current.

Superheterodyne Receiver

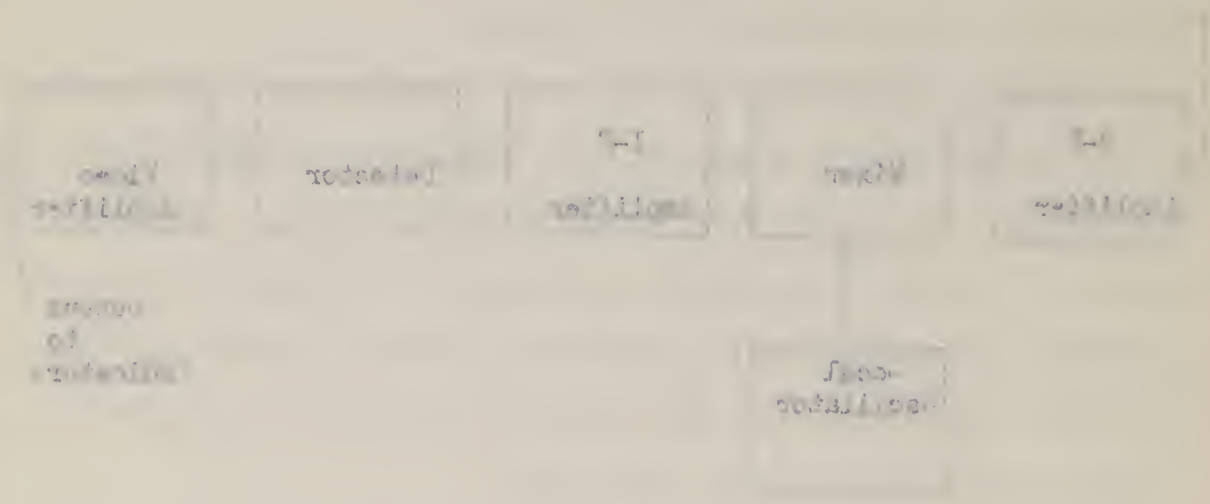
The receiving section of the radar set is required to amplify the input signal millions of times before the signal is of sufficient strength to apply to an indicator circuit. To obtain such high amplification, the signal may be passed through as many as twenty-five or more separate stages. Any number of stages may generally be classified under one of the six sections shown as Fig. 16.



(Fig. 16). Stages necessary in reception

(A) Amplifier and Mixer

The first stage of reception, radio-frequency amplification, is used only at the lower frequencies, since it is not peactical to attempt to amplify frequencies greater than several hundred megacycles per second directly. At the lower frequencies, grounded-grid triodes are commonly used to amplify the input. The input is applied between the cathode and the grid, and the output is taken off between the grid and the plate. In



this type of amplifier the plate-to-grid capacitance acts as a plate load instead of a feedback circuit, and the only possible feedback to produce undesired oscillations is the small plate-to-cathode capacitance. The lighthouse tube (446), specifically designed to amplify frequencies up to 1000 megacycles per second, is sometimes used in this stage of reception.

The amplified signal is then passed into a frequency conversion stage which "mixes" the input signal with another signal generated in the receiving section itself. The frequency of the locally generated signal differs by a fixed interval from the frequency of the echo signal, and if the sum of the strengths of these two signals is applied between two input terminals of a mixer, the output will be a new frequency equal to the difference in frequency between that of the input signal and that of the locally generated signal.

At the lower radar frequencies the mixing is commonly done by means of a triode. Multi-grid tubes, such as those used in radio superheterodyne receivers, are not used, since they introduce a high noise factor. The triode is normally biased at cut-off, with the sum of the input and locally oscillated signals being applied between grid and cathode. To preserve the strength of the input signal, the input of the mixer is tuned to the input signal frequency. And the local oscillator voltage is only loosely coupled to the tube's input. The output of the mixer is tuned to the new intermediate frequency.

At the higher frequencies used in radar work, the received signal is fed directly to the mixer without amplification, and the silicon crystal mixer has been found the most effective method of preventing excessive noise from being introduced. The crystal mixer, used in all radar sets operating

at frequencies greater than 3,000 megacycles per second, is composed of a small flat piece of heat-treated silicon and a fine wire tungsten cat whisker, both mounted in a small cartridge. The received signal is fed directly to the crystal by means of a coaxial line. The local oscillator frequency is fed into the receiver transmission line by means of an adjustable flat-coupled plate.

The intermediate frequency output of the mixer is fed directly into a coaxial cable, and suitable precautions are taken to see that the i-f load does not interfere with the application of the echo signal and the local oscillator circuit to the crystal. Also, great care must be taken to see that the local oscillations are coupled into the transmission line loosely enough so that no harm is done to the crystal or to the strength of the input signal.

(B) Local Oscillators

Any of the standard oscillator circuits may be used to generate the mixing frequency required by the lower radar frequencies, the principal requirement being that the oscillations be highly stable. As we move into the extreme ultra high frequency region, the use of triode oscillator circuits presents the same difficulties that were discussed in Ultra High Frequency Oscillators, Section IV, and new methods have to be devised. The most common method used to generate ultra high frequency waves in the receiving system at frequencies above 3,000 megacycles per second is the reflex-velocity modulator tube.

The standard reflex-velocity modulator tube is composed of four sections: a cathode, a control grid, a resonant cavity, and a repeller electrode. The essential circuit diagram of such a tube is shown in Fig. 17.

of frequencies greater than 3,000 megacycles per second, it consists of a small flat piece of quartz-tourmaline silicon and a flow wire [illegible] and [illegible], both mounted in a small cartridge. The received signal is fed directly to the crystal by means of a coaxial line. The local oscillator frequency is fed into the receiver transmission line by means of an adjustable [illegible] coupled [illegible].

The intermediate frequency output of the mixer is fed directly into a coaxial [illegible], and suitable precautions are taken to see that the 1-f load does not interfere with the [illegible] of the echo signal and the local oscillator circuit to the crystal. Also, great care must be taken to see that the local oscillations are coupled into the transmission line loosely enough so that no [illegible] is done to the [illegible] or to the strength of the [illegible] signal.

(b) Local Oscillators

Any of the standard oscillator circuits may be used to generate the filling frequency required in the lower radar frequencies. The principal requirement [illegible] that the oscillations be highly [illegible]. As we [illegible] into the extreme [illegible] frequency region, the use of [illegible] oscillator circuits presents the same difficulties that were [illegible] in the high frequency oscillators, section IV, and new [illegible] have to be [illegible]. The [illegible] method used to generate [illegible] high frequency [illegible] in the receiving [illegible] of frequencies above 3,000 megacycles per second is the [illegible] modulator [illegible].

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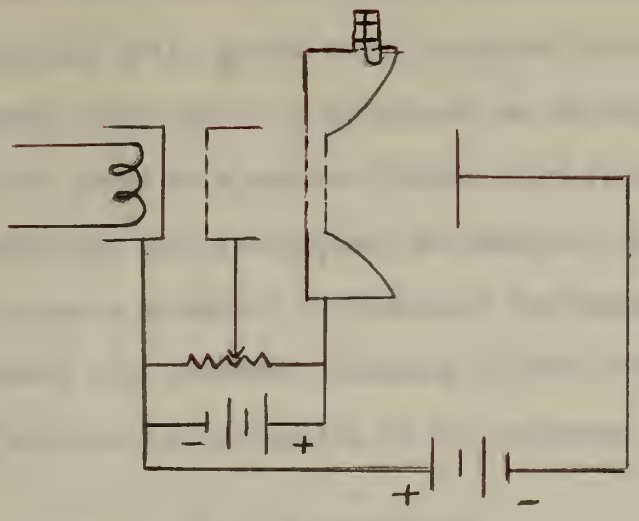


(Fig. 17). Reflex-velocity modulator tube.

Electrons emitted from the cathode are accelerated towards the positively charged resonant-cavity. Since the middle of the cavity is composed of a grid-like structure, many of these electrons continue through the grid towards the repeller plate. This plate is maintained at a sufficiently negative potential to reverse the direction of the electrons' paths before they actually strike the surface.

When the resonant-cavity is subjected to a high frequency alternating voltage, the instantaneous potential of the cavity relative to the cathode fluctuates, and electrons emitted by the cathode are accelerated by various amounts. When the alternating voltage and the direct voltages add together, electrons leaving the cathode are greatly accelerated. When the alternating and the direct voltage subtract from one another, electrons leaving the cathode are retarded.

If conditions are adjusted correctly, the retarted electrons will move just a small way past the cavity and return at the same time as the

accelerated electrons, which have had to procede almost all the way to the retarding potential grid, before being repelled towards the cavity.

The energy of this group of electrons can be delivered to the resonant-cavity, and thus serve as a source of ultra high frequency oscillations - if these bunches (as they are called) are made to return to the resonant-cavity when it has a potential sufficiently low enough to retard the motion of the electrons. The resonant frequency of this tube may be changed quite radically by changing the potential of the reflector plate.

(C) I-F Amplifiers

From the mixer the intermediate frequency is applied to several stages of amplification. Since the amplification must be very large, feedback and self-sustained oscillations between the successive stages must be avoided by the use of suitable filters and shielding devices.

Although a certain amount of distortion in the received signal is permissable, it is highly important that the amplification process preserve the steep leading edge of the signal, for this edge is the means of determining an accurate measure of target range. The ability of the i-f amplifier to preserve the exact shape of the input signal is dependent upon the band of frequencies which the amplifiers are allowed to pass - the wider the frequency range allowable, the more nearly perfect the reproduction of the input. The result of having a wide frequency bandwidth in the amplifier stages is the introduction of a large amount of noise in the output.

Consequently, a compromise between these two effects must be made, and the frequency range amplified in the frequency stages varies greatly from one radar set to another. The receiving section of the MPG-1 radar set

passes a range of intermediate frequencies slightly over eleven and one-half megacycles wide. The nine tubes in the intermediate frequency of this set are divided into three distinct groups. In each group one tube is tuned to 30 megacycles, another to 24.8 megacycles, and the third to 36.3 megacycles. The triplets are adjusted to give nearly equal output by changing the bandwidth and the gain of the individual stages. Most of the i-f frequency amplifiers operate over a considerably narrower range.

The individual amplifier stages are usually coupled by single inductively tuned circuits; the amount of gain varies between 7 and 20 times per stage. The most commonly used tubes are high trans-conductance tubes like the 6 AC 7. The intermediate frequency is normally above 10-60 megacycles per second.

(D) Detectors

The amplified intermediate frequency is then passed into a detector stage which serves the same purpose as the detector in the ordinary radio circuit. The detector is a rectifying device designed to preserve the envelope of the input voltage waveform, while at the same time it prevents the intermediate frequency from passing on into the video amplification stage. It is commonly a diode or a triode vacuum tube, and since it operates as an approximate linear device for relatively large input voltages (3 or 4 volts), the signal applied to it from the i-f amplifier stages must be at least that large.

The simplest method of detecting is in the use of a diode whose output is connected to a resistance and a capacitance in parallel. The diode rectifies the input intermediate frequency signal, and a voltage drop, proportional to the envelope of the input signal, occurs across the output

resistance. The high frequency compounds of the rectified signal are by-passed by the condenser.

The output signal is then taken off across the resistance, and may be removed as either a negative or a positive envelope, to pass to the video-amplifier by reversing the polarity of the diode. The principal requirement of a diode used for this purpose is that it have low cathode-to-plate capacitance, and that its plate resistance be low-compared with resistance on the output circuit.

The triode may also be used in the detector system by keeping the tube biased at cut-off, thus allowing the tube to act as a rectifier. Then the operation is quite similar to that of the diode detector. The output of the triode may be removed as either a negative or a positive pulse, by connecting the load impedance in either the plate or the cathode circuit.

(E) Video Amplifiers

The final stage which the received signal must go through in the receiving section is the video amplifier stage. The amplifying current is a resistance-capacitance-coupled amplifier with a nearby constant gain from 100 cycles per second through several million cycles per second.

Since the detector requires an applied voltage of several volts, and since the indicator usually requires less than 100 volts for efficient operation, most of the echo signal amplification is done in the intermediate frequency stage, and only one more stage beyond the detector is required. Indeed, if proper precautions are not taken, the signal applied to the video amplifier may be strong enough to block the amplifier and prevent it from passing the weak signals that follow.

To preserve the shape of the input, the amplifier must have both a good high frequency response and a good low frequency response. It is desirable to use pentodes in this stage, although the signal cannot be amplified as greatly by a single pentode as by other types of vacuum tubes.

T-R Box

There are many advantages in having the same antenna system serve as both transmitter and receiver. The weight of the radar set can be greatly reduced. The mechanical arrangements that are necessary to move the transmitting and receiving antennas in synchronism are not necessary. Moreover, the size of the radar set may be greatly diminished, for the transmitting antenna must be large in order to give high beam directivity, the area of the receiving antenna must be large to pick up weak signals. The amount of size duplication can be greatly reduced if one antenna system serves both purposes.

The transmitting system of the radar set is built to handle huge amounts of power; the radiated energy is measured in hundreds of kilowatts; while the receiving system is highly sensitive, sensitive enough to pick up returning energy whose power may be only a fractional part of a micromicrowatt. To make the same antenna system serve as both transmitter and receiver, the receiving section must be disconnected while the pulse is being radiated, and the transmitting section disconnected while the set listens for returned energy.

The T-R (transmit-receive) box is commonly used to disconnect the receiver and transmitter at the proper times for all frequencies below 3000 megacycles per second. The most essential part of the T-R box is a T-R tube, composed of two conical electrodes. This tube is placed within a resonant-

cavity tuned to the frequency of the output wave signal. When the transmitted energy is applied to the resonant-cavity through a coupling loop, the cavity resonates and the high potential difference built up across the conical electrodes causes a spark discharge almost instantaneously. The high voltage spark disrupts the resonance effect, and causes the collapse of the magnetic and electric field distributions within the cavity. As a result, no signal can be taken out of the cavity to the receiver. During reception the cavity again resonates, but the field strength set up is not sufficiently strong to ionize the dielectric between the two conical electrodes, and cause a spark.

An anti-T-R box is used to prevent loss of the received signal strength to the transmitting system. The anti-T-R box, identical in design with the T-R box, is placed at the proper distance away from the junction of the transmission and receiver lines to effectively block the received signals. During transmission, the anti-T-R box is fired by the strong output energy pulse and allows the pulse to pass by to the antenna system.

The T-R box is not a complete insulating device between transmitter and receiver, and at high peak power levels the T-R box may let enough power through to the receiver to damage the crystal mixer. In these sets Pre-T-R boxes are used to prevent excessive power from being passed to the crystal.

For the longer radar wavelengths, approximately the same type of system is used to protect the receiver against the power of the transmitted pulse. The T-R devices are usually short lengths of resonant coaxial or open-wire lines, with the T-R tube replaced by a spark gap.

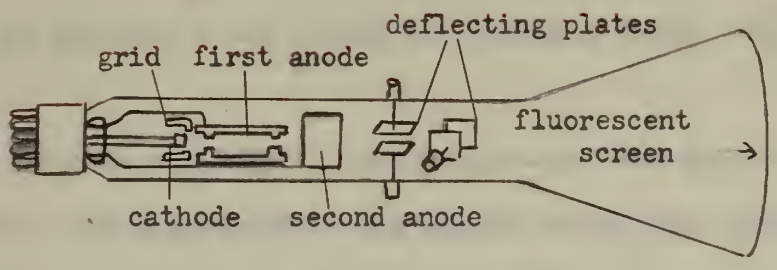
INDICATORS

Cathode-Ray Tubes

All the information collected by the radar set, regarding the distance and the direction of the target, is presented to the radar operator by means of the indicator. In almost all radar sets the information is presented visually, and the indicators are cathode-ray tubes. Since any single cathode-ray tube is capable of presenting two, and only two quantities on its screen at one time, the number of cathode-ray tubes used will vary from one set to another, and will depend upon the exact target information desired.

The cathode-ray tubes used in radar are the same in principle as those used in other technical fields. The three essential elements are: (1) a cathode-ray gun which can produce a narrow beam of rapidly moving electrons; (2) a fluoresent screen which glows under the impact of an electron stream; (3) a device which is capable of deflecting the beam and displacing the luminous spot on the screen. Deflection of the electron stream is done by applying a varying electric or a varying magnetic field to the neck of the tube. Both methods are used in radar equipment. The tubes are called electromagnetic or electrostatic cathode-ray tubes, according to the deflection method used.

A cathode-ray tube frequently used in radar work is shown in Fig. 18. Although the electric beam in the tube is deflected by a varying electrical field, the basic steps involved in generating a narrow electron beam are the same as those in the electromagnetic tube which is quite similar. The source of electrons is thermionic emission from the cathode. The electrons



(Fig. 18). Cathode-ray Tube.

then pass through a control grid which focuses the electron flow slightly, and by controlling the number of electrons passing through, controls the brilliancy of the beam at the screen. Control of the electron flow by this grid is effectively utilized in intensity modulation, and the control proves to be a very satisfactory means of displaying target information.

The first anode acts like a converging lens, and is used to focus the electron stream. The second anode serves to accelerate the electrons, and thus determines the velocity with which the electrons will strike the screen. The voltage on the first two plates is varied when necessary, to bring the beam into focus; the voltage on the second anode is ordinarily held constant throughout the operation of the tube.

The electron beam may be deflected by applying a potential difference across either of the two pairs of plates shown in Fig. 18. These pairs of plates are insulated from the other electrodes in the tube, and are provided with separate terminals. When a difference in potential is applied between a pair of plates, the electron beam is pulled towards the plate with the higher potential.

The deflection which results is proportional to the applied voltage. A third anode is sometimes used beyond the deflection plates, to force the electron beam to accelerate and strike the luminous screen with greater intensity.

The deflection sensitivity of the cathode-ray tube depends upon the velocity given to the electrones by the second anode, also upon the length of the deflecting plates. The deflecting sensitivity can be increased, while leaving the velocity of the electrons unchanged, by making the deflecting plates parallel for part of their length, and slightly divergent during the remainder.

Electromagnetic cathode-ray tubes differ slightly from the electrostatic tube just described. Normally, electromagnetic cathode-ray tubes use magnetic focusing devices. The deflecting force is created by passing a current through coils of wire wrapped about an iron core and placed about the neck of the cathode-tube. The deflection produced by a magnetic field is normal to the direction of the field, and proportional to the magnetic field strength.

The screens used in cathode-ray tubes are coated with a very thin layer of luminous material. When a stream of electrons bombards the screen, the luminous material becomes fluorescent, and emits light. If the material continues to emit light for a length of time after the bombardment ceases, the material is said to be phosphorescent.

Several types of fluorescent material are used in radar cathode-ray tubes. A few of the more common types of material are: willemite, zinc oxide, and zinc sulphide mixed with cadium zinc sulphide. The duration of the fluorescent period and the color of the emitted light vary with the

material used. The colors emitted by the three fluorescent materials listed above are green, blue and white, respectively.

The brilliance of the fluorescence will depend upon the number of electrons hitting the screen, and the energy of the electrons hitting the stream.

The impact of the electrons on the screen has a second effect. It is sufficiently strong enough to cause secondary emission of electrons, and a means must be devised to remove them. By coating the interior of the tube envelope with graphite, and by connecting this coating to the anode, the secondary emission electrons can be collected and removed from the cathode-ray tube. The coating also serves to protect the electron beam itself from the effects of any stray electrostatic or electromagnetic fields.

The electromagnetic cathode-ray tube has certain advantages over the electrostatic tube. It is generally more rugged in design, therefore is more reliable for mobile equipment. Its tube length for the same size screen is smaller; therefore less over-all space is required for the equipment used. On the other hand, the electrostatic tube is lighter, and requires little or no external deflective current or power.

The size of the cathode-ray tube's viewing screen is seldom less than five inches in diameter, and larger screens are used. The distortion introduced as the deflection becomes greater, usually limits the diameter of the screen to less than 16 inches in diameter.

Type A Indicator

There are many ways through which the cathode-ray tube may be used to indicate the range or the position of the target. One of the simplest and most widely used is the Type A presentation which gives the observer an

accurate measure of the distance of the target.

In this type of presentation, the cathode-ray beam sweeps horizontally across the screen at constant velocity from left to right. (The "fly-back" of the beam is generally blacked out, and consequently has no effect upon the pattern on the scope).

When the echo signal received by a set is amplified, and applied to the vertically deflected plates of this tube, a sharp V-shaped "pip" is formed on the horizontal time base. If the start of the cathode-ray sweep is properly synchronized with the pulse transmitter, the distance of the "pip" along the horizontal time base is a measure of the distance of the target.

The horizontal deflection of the cathode beam is obtained by applying a saw-tooth voltage wave to the horizontally deflecting plates of the electrostatic cathode-ray tube. The deflection, and thus the sweep on the screen, will be perfectly linear if the deflecting voltage increases at a linear rate.

The original stage in the production of the saw-tooth voltage wave is generally a multivibrator circuit. When triggered by a signal from the basic time-controlling circuit of the set, the multivibrator produces a box-like, rectangular pulse, whose duration is determined by the resistance and the capacitance values of the circuit (see Section III). The duration of the output pulse of the multivibrator will determine the maximum range that is to be shown on the cathode-ray screen.

The box-like voltage pulse produced by the multivibrator is applied to a sweep generator which changes the rectangular pulse into an almost linear rising voltage. This voltage may then be amplified if necessary, before applying it to the deflecting plates. It is generally desirable to operate the horizontal deflection plates in push-pull fashion to minimize distortion

and lack of focus on the screen.

The return sweep of the cathode-ray beam is "blacked out" by applying a highly negative pulse to the grid of the cathode-ray gun. This pulse is usually obtained directly from the multivibrator circuit mentioned above. The application of the high negative pulse to the grid, decreases the number of electrons striking the screen, to the point where they do not cause fluorescence.

The echo signal for the receiver section is applied to the upper of the two vertically deflecting plates, and causes the "pip" to appear. The intensity of the input signal will determine the amount of beam deflection caused. It is possible to use this type of radar indicaor as an approximate target position indicator by moving the antenna until the deflection on the screen, caused by the returning signal, appears to be a maximum.

The length of the time base of the Type A indicator is limited by the size of the cathode-ray tube's screen. If too large a time is involved between the transmitted pulse and a returned echo, the screen must be made larger or the time scale diminished. To increase the length of the scale while, at the same time, using the same size screen, a circular time base is sometimes used. The target "pips," then appears on the circumference of a circle; the distance between the transmitted pulse and the echo, being a measure of the target's range. The principal disadvantage of this type of presentation system is that it tends to be confusing and hard to interpret.

It is usually desirable to superimpose upon the target information, a marker indicating the target's range. The marker may be a movable step or notch in the horizontal sweep of the cathode-ray beam or may be a series of vertical lines separated by fixed time intervals and representing equal

and lack of focus on the screen.

increments of distance.

The movable range step is readily obtained by the use of the one-shot cathode-coupled multivibrator. By properly choosing the resistance values in this type of circuit, we can make the output pulse duration be very nearly a linear function of the voltage applied across the first tube. When an output pulse from this multivibrator, shorter in duration than the sweep time, is applied to the vertically deflecting plates, there will be an abrupt break in the horizontal sweep - and one part of the sweep will be displaced vertically from the other. By varying the voltage applied across the first tube of the multivibrator, the output pulse duration can be changed and the step made to move across the sweep. If the voltage adjustment apparatus is calibrated in distance, the step can be moved to coincide with the leading edge of the echo pip and thus indicate easily and accurately the distance of the target.

A series of range markers can also be superimposed upon the horizontal sweep if desired. These markers also originate from a multivibrator circuit which generates a rectangular box-like pulse. The pulse from the multivibrator is applied to a high frequency oscillator which oscillates only during the duration of the pulse. The high frequency oscillations after being passed through clipping, squaring, and peaking stages, can be applied to the vertically deflecting plates where they cause periodic vertical markers.

Type P Indicator

The Type P Indicator makes it possible to view on the same screen the range and the azimuth of all targets surrounding the radar set. The only requirement which the target must meet is that it return strength to the

receiver. This type of indicator is commonly called the PPI, or plan position indicator, since the target information is presented to the observer in map-like form.

In the PPI presentation, the cathode-ray beam starts at the center of the screen and is deflected radially outward with a constant velocity. The velocity of the beam, as in Type A indicator, is determined by the size of the screen and the maximum distance to be measured. The direction of the radial sweep is always made to correspond to the azimuth angle of the radar antenna.

The bias of the cathode-ray tube is such that no appreciable fluorescent occurs on the screen until an echo signal is received. The echo signal, after being properly amplified and applied to the grid, causes an increase in the number of electrons striking the screen. As the antenna is rotated about a vertical axis, the PPI sketches a pattern on the screen, that is composed of light and dark blotches. The light blotches indicate the presence of a target; their distance from the center represents their distance from the radar operator, and their position on the screen represents their position, relative to the observer.

In this type of set it is essential that a phosphorescent material be used on the screen, to hold the image of the target until the radially deflected beam has completed its cycle around the complete area of the screen.

The necessary persistence is usually obtained by using two layers of material on the screen instead of one. The layer which the electron beams actually strike emits a brilliant blue flash of light under the impact of an electron stream. Underneath, between the first layer and the tube's

envelope, is placed a layer of phosphorescent material which is excited by the blue flash, and emits a yellow light for an appreciable length of time.

Usually electromagnetic cathode-ray tubes are used to focus and control the deflection of the electron beam used in the PPI. The radial deflection of a beam is caused by applying simultaneously saw-tooth waves of current to the vertical and horizontal deflection coils. The beam will be deflected along the direction determined by the relative strengths of the two signals.

To force the beam to rotate about the center while being deflected radially, the saw-tooth current waves applied to the deflection coils are modulated with sinusoidal envelopes, thereby causing the deflection field to rotate. Radial deflections may occur as many as 17,000 times before the cathode ray repeats a previous path.

The generating of the saw-tooth current waveforms, used in deflecting the cathode-ray, starts when a trigger pulse from the time control circuit is applied to a multivibrator. The rectangular wave produced is then applied to the grid of a triode, which serves as the primary saw-tooth wave generator. The output saw-tooth wave is taken off across a condenser connected between the plate and the cathode.

The basic saw-tooth waves are then divided into two groups; one will eventually furnish the source of current for horizontal magnetic field deflection, and the second will furnish the source of current for the vertical magnetic field deflection.

After sinusoidal modulation, the saw-tooth waves are amplified if necessary, and passed through phase inverter stages to allow them to be used in push-pull operation. The last stage before applying voltages to the

deflecting devices is to clamp the four voltages into proper phase. This process is used to make sure that the radial deflection pattern will start for the center of the screen.

The input signal or echo signal, which is of primary interest to the observer, is placed upon the screen by the use of intensity modulation. The received signal, which usually passes the indicating section as a negative pulse, is inverted and applied to the grid of the cathode-ray tube. The result allows a more intense beam of electrons to strike the screen and produce a more intense luminous spot at this particular section of the screen.

It is possible to superimpose upon this screen a series of range marks which aid in determining the exact distance of the target from the observer. Thus markers on a PPI indicator would appear as narrow bright line circles on the screen of the cathode-ray tube. They may be introduced by a periodic positive pulse, applied to the grid at a certain fixed time interval, after the start of each pulse.

CONCLUSION

Radar has an almost infinite number of military applications. Radar sets make bombing runs possible when aircrew bombadiers cannot see the ground below. Radar sets aim and control the fire of antiaircraft guns at targets which are invisible to the naked eye. Radar sets locate the flight of buzz bombs and trace their path through the air.

But what are the possible applications of radar today? What are the possible applications in aeronautics?

The applications are, of course, much more limited. Radar sets are expensive, both to build and to operate. In times of war, cost means nothing; performation means everything. In times of peace, cost and performance must balance if the equipment is to be used. Moreover, radar sets are particularly important in picking out the path of a target which wishes to escape observation. When, in times of peace, the target does not desire to hide, but instead, wishes to make its presance known, the radar set ceases to be quite so important.

The principal peacetime use to which radar has been put is air traffic control; the most effective peacetime use is guiding airplanes onto runways under low visibility conditions. This method of control was widely used during the most recent war and was called Ground Controlled Approach (GCA).

Two complete radar sets are required for this type of landing control, and they are usually placed just off the edge of the runway. The search radar set, as one of them is called, is rotated constantly about a vertical axis, and is made to scan the area 20 to 30 miles around up to a height of 4,000 to 5,000 feet. The second radar set is used to control the actual

let-down of the airplane, and it sends a highly directive beam at a slight angle along the runway. The narrow beam can be deflected slightly up and down, or back and forth as is necessary, but only through a limited range.

The search radar set locates all airplanes in the area of the airfield, and presents the information to the radar operator on a PPI screen. The pulse duration of the search radar beam varies, but is usually quite small, and about 0.5 microseconds. The ground operator, after noting the position and elevation of the various planes, selects the first plane to be landed, and procedes to "talk it down." The ground operator follows the path of the airplane on the search radar scope only until he can pick it up on the sharper, second radar scope. The power of the second radar set is sufficiently strong to detect the presence of a target at about five or ten miles away if it is in line with the runaway. The actual landing directions are obtained from the screen of this second radar scope.

The second radar set uses a highly directive beam that scans only a limited area above and on each side of the runway. Quite frequently conical scanning is used by this radar set to allow the most precise position-locating ability possible. The ground operator, by watching the indicators of the set as the plane glides in, is able to tell the pilot the corrections necessary in the actual glide path to bring him directly down on the end of the runway. Since the radar indicator itself usually indicates the azimuth error in degrees, and the elevation deviation in feet, of the plane, in relation to the correct glide path, all the observer is required to do is relay the information to the pilot.

In this type of radar work, the only equipment necessary on the airplane is the regular air-to-ground communication equipment. All other equipment

is located on the ground.

Radar equipment has also been used in aeronautics in anti-collision devices. The equipment, weighing about 100 to 150 pounds, has a range of well over 200 miles, and is unaffected by banking, climbing, or driving of an airplane to which it is attached. The most effective methods by which collisions may be prevented still seem to be done from ground control.

Loran is commonly considered under the term radar, and it has proved to be a successful means of long distance navigation, particularly over the ocean. Since loran does not depend upon the reflection of energy back to the transmitter, to indicate range, it cannot be correctly called a radar method.

Radar has served an extremely valuable purpose, and has opened up new vistas in the electromagnetic spectrum. The old land-line telegraphy system is soon to be replaced by new radio wave methods, using the same principle as radar. The planets in outer space may now be studied by sending sharp pulses of ultra high frequency energy into space. The distance of the moon from the earth has been established by radar methods, and the determined value checks closely with the value obtained by other methods. Soon, we shall know whether the moon is made of green cheese!

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